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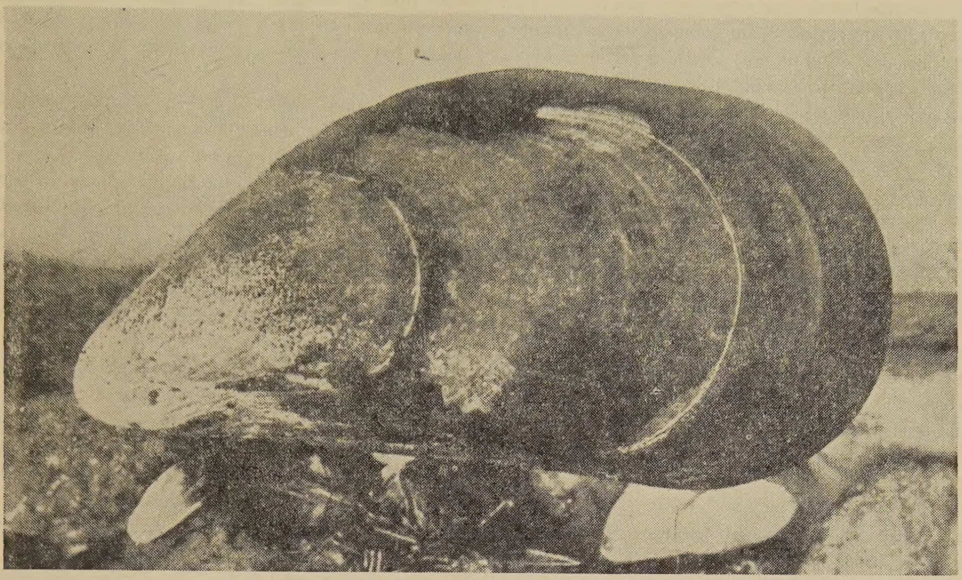

FIG. 1 EXTERIOR VIEW OF COMMON MUSSEL, MATURE FORM

# Some Biological Fundamentals of Marine Fouling

BY WILLIAM F. CLAPP,[1] DUXBURY, MASS.

**The common mussel is identified as the organism most important in the fouling of sea-water conduits and most difficult to control. Relevant features of its construction, living habits, rates of propagation and growth, and methods of locomotion and self-protection are described. While very young organisms, in general, are less resistant to unfavorable conditions than the mature of their respective kinds, and the mussel is probably no exception; in the case of the young mussel very high resistance is found very shortly after the permanent shell takes complete formation. Chlorination tests on mussels at Kure Beach, N. C., are described and results quoted.**

## Classification of Fouling Organisms

THERE are a number of different kinds of marine animals and plants which can be classed as fouling organisms. They can be divided into two important groups; those which are sessile or incapable of further movement after having become attached and those which can become secure or optionally motile. In the first group would be included such common fouling organisms as the barnacles, bryozoans, and algae; in the second, the common mussels and sea anemones.

Those in the first group are unable to escape from an environment which is no longer favorable. Those in the second group are capable of migrating from an undesirable location and of locating again and becoming firmly attached where the surroundings are more suitable for the support of the organisms.

Among all of the organisms which might be classified as fouling,[2] the one group which generally appears to be most difficult to control is that of the mussels, typically shown in the mature form in Fig. 1. The various species in this group are frequently able to survive conditions which eliminate other groups of fouling organisms. Therefore the remarks following will be confined to the mussel, and it is believed safe to assume that in so far as organisms which are of real importance in the marine-fouling problem under discussion are concerned, methods or materials which will check fouling by mussels will be at least equally effective in controlling the other organisms.

Among the various species of mussel which are found commonly and plentifully in intake systems, the edible mussel, *Mytilus edulis*, is probably the worst offender. It has a very wide distribution along the Atlantic coasts of Europe and the United States, and also on the California coast. Other common species of fouling mussel are *Mytilus californicus*, *Mytilopsis leucophaeta*, *Brachydontes exustus*, and *Brachydontes recurvus*.

## Usual Habitat of the Sea Mussel, Mytilus Edulis

*Mytilus edulis* normally lives and thrives in enormous numbers in water with salinities varying between 15,000 ppm and the 30,000 ppm or more of normal sea water, in the between-tide

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[1] President, William F. Clapp Laboratories, Inc.

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—S-15.

[2] "Macro-Organisms in Sea Water and Their Effect on Corrosion," by W. F. Clapp, The Corrosion Handbook, H. H. Uhlig, editor, John Wiley & Sons, Inc., New York, N. Y., 1948, p. 433.

"Fouling Organisms on Paints in Salt Water," by W. F. Clapp, Protective and Decorative Coatings, J. J. Matiello, editor, John Wiley & Sons, Inc., New York, N. Y., vol. 3, 1943, p. 401.

areas in more or less sheltered harbors and estuaries. The *Mytilus* also thrives, with appropriate conditions of environment, at considerable depths. Individuals may exist in water of lower salinity, but under such conditions comparatively few survive. Therefore those present under conditions of low salinity are so few in number that they contribute very little to fouling.

In harbors where conditions are favorable, *Mytilus edulis* frequently will form great "beds" several acres in extent on the mud flats which are exposed at low water. In these beds mussels of all ages and sizes are fastened together in clusters which may contain hundreds of individuals to the square foot.

While it is true that such mussel beds are also found below the mean low water and even at considerable depths in the open water outside of harbors, it seems probable that the heavy growths of mussels frequently found in intake tunnels are formed by the offspring of the parents living in the mussel beds in the shallow harbor water in the neighborhood of the intake tunnel.

## Physiological Factors and Development of Mytilus Edulis

The sexes are separate. The female *Mytilus edulis* may produce considerably more than 1,000,000 eggs in a single season. After fertilization, cell division and the development of the free-swimming embryo are rapid. The duration of this development of the *Mytilus* free-swimming larva, up to the appearance of the first embryonic shell, varies considerably. Some investigations have shown that this period of growth may be completed in as brief time as 12 days, while in other cases the same development requires more than 3 weeks. This variation appears to be normal and undoubtedly is due to favorable or unfavorable conditions of temperature and other factors.

During the period of larval development the embryos are not attached, in fact, are not sufficiently developed to have formed any organ which could be used for the purpose of obtaining a foothold. They may be carried back and forth by tides and currents and therefore may be widely distributed. When the embryo has formed the first protective shell it is approximately 0.25 mm in length. The shell is transparent and bears little resemblance to the second protective shell which the animal begins to form almost immediately beneath the original embryonic shell.

During the height of the breeding season these minute embryonic mussels, which have progressed to the shell form, may appear in great numbers on any material which provides a satisfactory foothold. Wooden panels placed in the water during the seasons when these larval forms are abundant frequently show great numbers of individuals which have arrived on the panels and are endeavoring to secure a firm foothold. While such "sets" generally occur during the late spring, summer, and early fall months, the past winter saw unusually heavy sets in December, January, and February, at Portland, Me., Atlantic Beach, N. Y., and other northern locations.

At Atlantic Beach, panels submerged for 30 days ending January 13, 1949, were found completely covered with the shelled embryos of *Mytilus edulis.* Many specimens had attained a length of 1 mm. The average number of individuals to the square inch was found to be more than 1000. Figs. 2, 3, and 4 are greatly enlarged views of mussels from the set at Atlantic Beach. These figures show young mussels in the two stages of development mentioned. The embryonic shell is clearly visible at the umbo of the larger specimens. Fig. 4 is of special interest showing juvenile mussels attached to a hydroid stock. It is possible that unusually favorable conditions during the past winter months have been responsible for the early development of embryo *Mytilus.* It is not known whether or not they are able to survive the unfavorable conditions of subsequent low temperatures and probably scanty food supply.

In the case of the normal mussel, 10 months after having become attached as a minute embryo 0.5 mm in length to any submerged object, an individual specimen of *Mytilus edulis* may grow to be more than 50 mm in length, 35 mm in width and 20 mm in thickness. Thus an individual may increase 1,000,000 times in bulk during a growing period of 10 months. It would also follow that if the majority of such embryos should

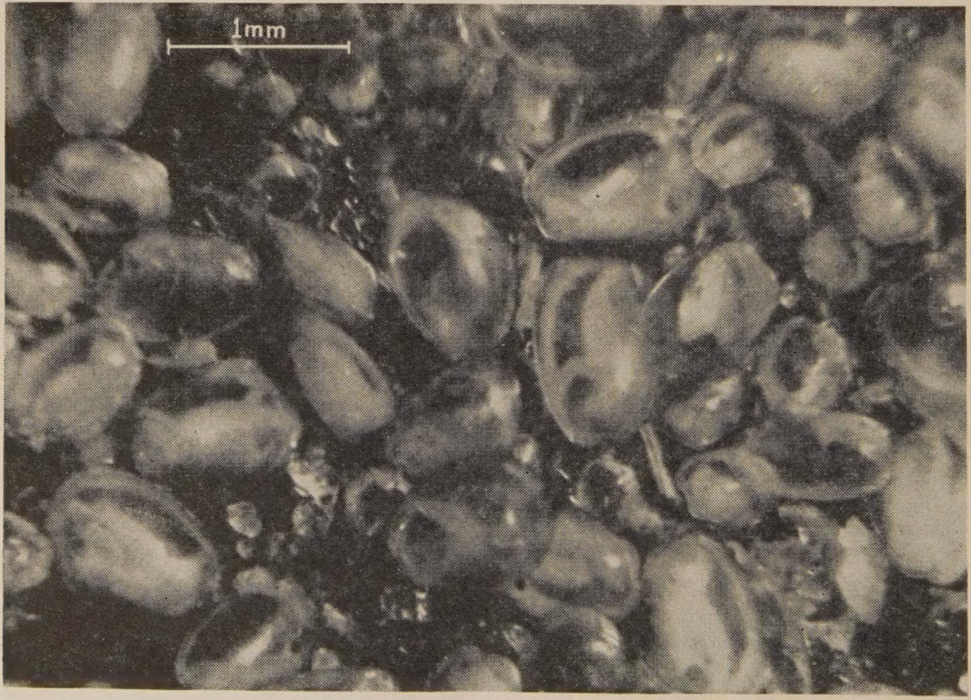


Fig. 2 Embryonic and Juvenile Mussel, Shown Clustered 8 to 10 Deep
(Collected at Atlantic Beach, N. Y., December 13, 1948–January 13, 1949.)

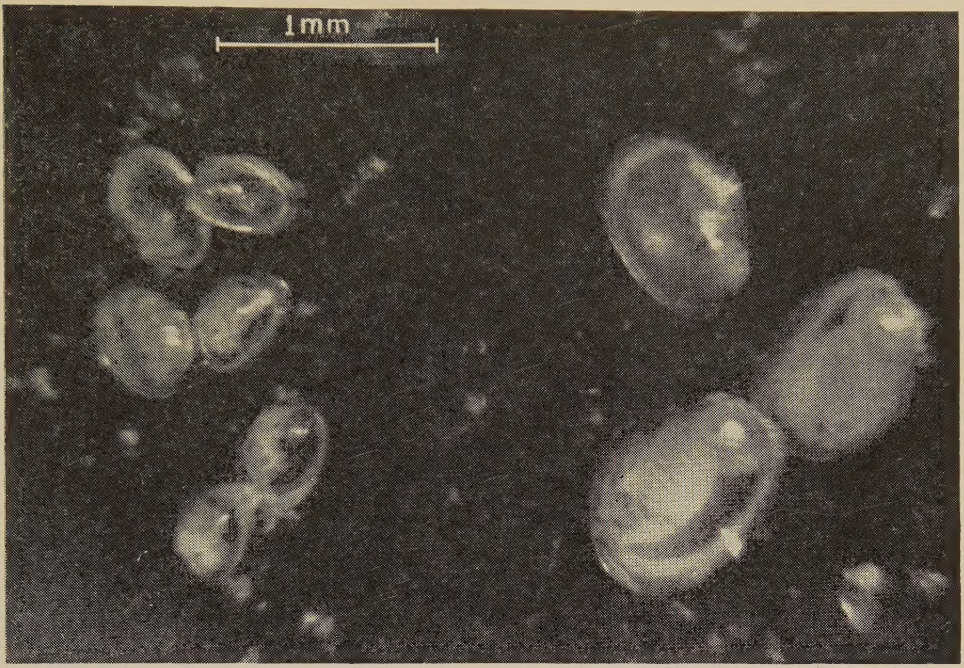


Fig. 3 Embryonic and Juvenile Mussels—Detached Individuals
(Collected at Atlantic Beach, N. Y., December 13, 1948–January 13, 1949.)

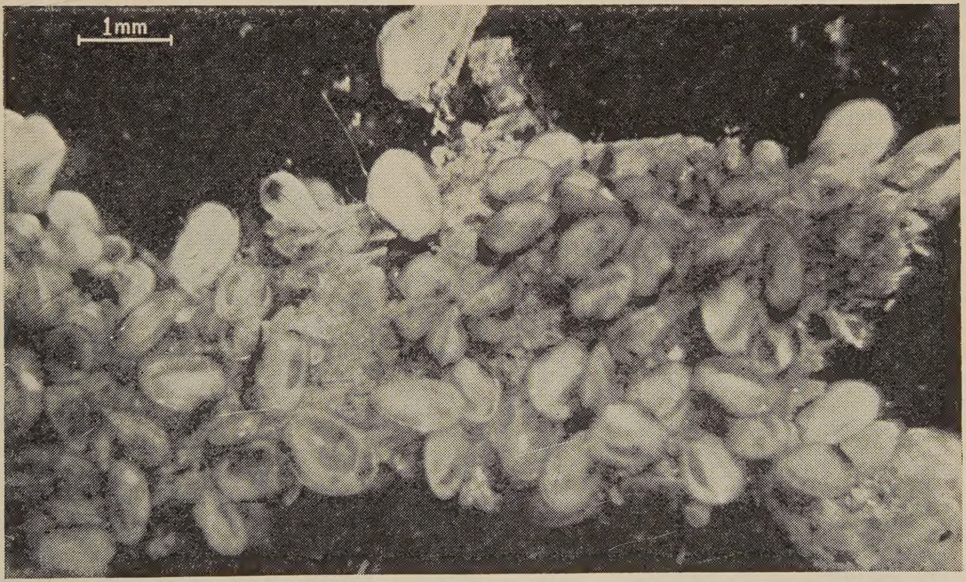


Fig. 4 Embryonic and Juvenile Mussels, 1 Mm Long or Less, Attached to Hydroid Stock, Clustered 8 to 10 Deep
(Collected at Atlantic Beach, N. Y., December 13, 1948–January 13, 1949.)

live, a pint of *Mytilus* embryos might, in the same period of time, develop into a mass of mature specimens weighing 500 tons or more.

## Relative Susceptibility of Young Mytilus Edulis to Unfavorable Environment

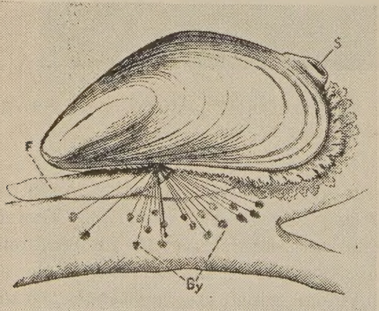
From numerous observations it seems certain that under normal conditions embryonic and immature *Mytilus edulis*, rarely more than a few millimeters in size, are responsbile for the *Mytilus* fouling in intake tunnels. The system of screens which usually is operated at the entrance of such intakes, would prevent passage of large specimens, and certainly would prevent passage of individuals large enough to be breeders. Therefore the efforts of those who have attempted to control mussel fouling have been to prevent the attachment and survival of the embryonic and immature individuals which are carried into the tunnel.

It has been generally believed and undoubtedly is true that with all organisms the mortality is highest in the embryonic or immature stages. The mature organism is stronger and better adapted to survive unfavorable surroundings than the very young of the same species. This is probably true also with *Mytilus edulis*. However, apparently in the case of *Mytilus* *edulis* a high degree of endurance is attained at a rather early age after acquiring the permanent shell. In certain studies made at the Kure Beach Test Station near Wilmington, N. C., and also in tests conducted by H. E. White,[3] the very young of but few millimeters in size of at least some species of mussel are found as capable of surviving under the described unfavorable conditions as the mature animal. At this stage the bivalve shells can be closed tightly for long periods of time, thus completely excluding any obnoxious materials which may be present in the water.

### Locomotion and Grouping of Mytilus Edulis

The *Mytilus*, like all other mollusks which are provided with such an organ, uses its single foot for locomotion. In young specimens 2 or 3 mm or less in length, the foot, when extruded, is of about the same length as the shell. Near the tip or outer end of the foot is a minute orifice through which the animal is able to extrude a very delicate filament quite similar to the strands of fine spider web. It is this web which provides the first "holdfast" for the immature mussel. By means of powerful muscles the foot can be moved in any direction, lengthened, or contracted at will. The motion of the foot in a mussel which is migrating from one location to another bears a striking resemblance to the motion of an elephant's trunk. When moving, the foot is extended to its full length, the tip end is arched, and the thread-spinning gland is touched to the surface of the material upon which the organism is moving. The thread is firmly cemented in the form of a minute pad to this spot, and it is sufficiently strong to support the weight of the entire animal and shell if suspended in the air. As soon as the thread is attached to the base, the foot is contracted and the shell is pulled forward until it is directly over the new point of attachment. Specimens which are as large as 5 mm in length are therefore capable of moving for a distance equal to the length of the shell at each time a new holdfast is formed. Since each forward movement may require only a few seconds, the total distance covered in an hour may be several feet. With still larger individuals, the length of the foot in proportion to the length of the entire shell tends to be smaller, progress so tends to be slower, and distance covered in a given period of time much less.

When the mussel has reached a spot where conditions are favorable, it remains stationary while the foot, waving around in all directions, exudes a large number of threads, known as the byssus, each of which is firmly cemented to whatever the gland of the foot comes in contact with and provides an attachment which is exceptionally secure. Fig. 5 is a drawing of a mature mussel showing the foot extended and a number of byssus threads attached. Fig. 6, also a drawing, shows the internal anatomy. Many of the holdfasts may be upon the base upon which the mussel is traveling, or upon the shells of other mussels or other organisms near at hand. The mussels customarily come to rest in large clusters with a mass of weblike holdfasts attached to the base and to each other, as illustrated for small clusters in Fig. 7. When conditions, for one reason or another, become unsuitable, the organism can cut its cables and again endeavor to move on. However, in large clusters it is obviously necessary that all individuals have the same urge to separate one from an-



*Mytilus edulis* L., attached by its byssus (By) to a piece of wood: F, foot; S, anal siphon, the branchial siphon being below it and not closed. (After Möbius.)

Fig. 5 Sketch of Exterior of Mussel, Showing Mantle and Foot Extended

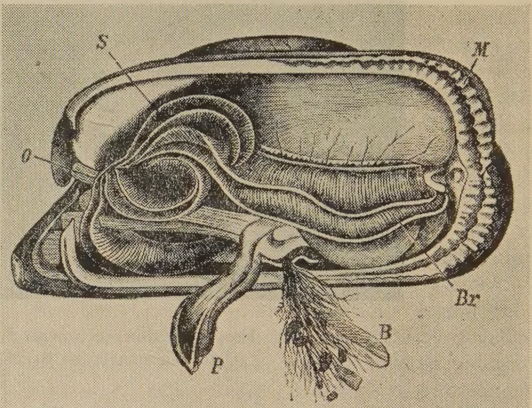


Fig. 758. — *Mytilus edulis*, Linné. Le lobe gauche du manteau est relevé. — *O*, bouche; *S*, palpe labial externe; *Br*, branchie; *P*, pied; *B*, byssus; *M*, bord du manteau (Deshayes).

Fig. 6 Diagram of Internals of Mussel

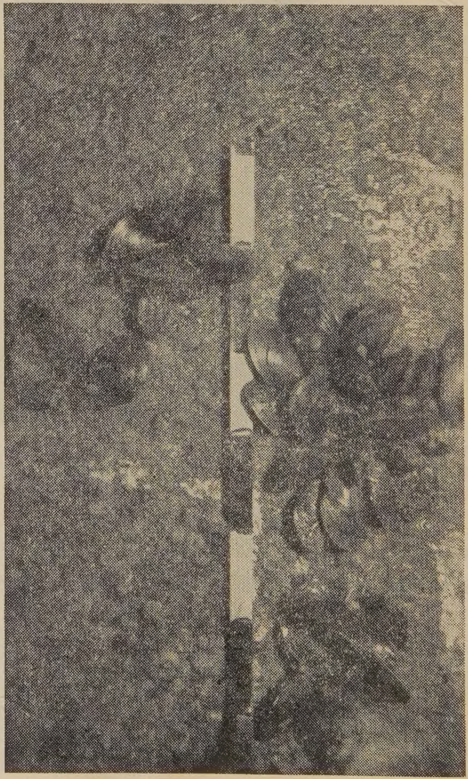


Fig. 7 Clusters of Mussels on Wall of Intake Tunnel
(Black and white scale divisions approximately 1 in.)

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[3] "Control of Marine Fouling in Sea-Water Conduits Including Exploratory Tests on Killing Shelled Mussels," by H. E. White, published in this issue of the Transactions, pp. 117–126.

other and from the base. Tests have shown that complete severing of all holdfasts in a cluster can be and frequently is accomplished in the comparatively brief period of only an hour or two.

There is one other important method of locomotion of which the mussels are capable. Young individuals of 4 mm or 5 mm or less in length are able to sever their holdfasts and float away from their immediate environment. By means of tides, currents, and winds they may in this way be carried for long distances. Having no power to direct their movements, their ultimate landing spot is a matter of chance. Incidentally, during a migration of this type, many individuals up to 4 mm or 5 mm in diameter may be carried through the screens and then manage to secure a foothold in some portion of an intake tunnel or system. It is believed that such small mussels are capable of retaining inside of the shell a small bubble of air or gas which enables them to float at will in the water. If the mussel is disturbed while floating, the bubble disappears and the mussel sinks rapidly to the bottom.

### Kure Beach Chlorination Tests

At the Kure Beach Station studies were undertaken to determine the comparative value of different schedules of chlorination in control of mussel growth. The procedure was to place a test tray in each group of identical weir boxes or compartments supplied with continuously flowing sea water. The general arrangement of the test equipment is shown in Fig. 8. Individual compartments were approximately 8 in. × 10 in. × 24 in. long. Turbulence was reduced by a perforated stilling baffle at the midlength. Water entering the different compartments was chlorinated to selected residual concentrations by automatic feeders on predetermined schedules.

In order to determine the comparative value of various strengths of chlorine in the control of fouling organisms when added to the circulating water for varying periods of time, the following procedure was adopted:

The organisms used was the *Brachydontes exustus*, one of the mussels commonly found in intake systems in southern waters. The normal habitat of this mussel is in the between-tide area, where they grow in such abundance that they frequently completely encrust wharf piling, bulkheads, and other structures in the open sea. The individual specimens can become so firmly attached to steel, concrete, wood, or other materials, that they cannot be dislodged even by the heaviest surf. As in the case of other species of mussel, the young are incapable of attachment to any surface until they have developed to the stage at which the embryonic shell has been formed and the organism has reached a length of 0.25 mm or more.

Clusters of the mussels, containing from 50 to 100 specimens of lengths varying from 0.5 mm to 35 mm, obtained from the between-tide area of a sheet-steel bulkhead, were used in the test. Care was taken not to injure the specimens by rupturing the byssus gland in the foot. By means of a scalpel the byssus threads were cut as closely as possible to the pads on the tip ends of the threads. The clusters were then placed in separate porcelain dishes and the dishes submerged in clean flowing sea water. Within an hour or two the clusters had become sufficiently firmly attached to the extent that they could only be removed with difficulty. At the end of 24 hr the clusters could not be shaken loose from the containers. The dishes were then distributed in the various weir boxes as follows:

Box No. 1—Nominal chlorine residual, 0.00 ppm...Control
Box No. 2—Nominal chlorine residual, 0.25 ppm...Continuous
Box No. 3—Nominal chlorine residual, 0.5 ppm...Continuous
Box No. 4—Nominal chlorine residual, 1.5 ppm...2 hr on: 2 hr off
Box No. 5—Nominal chlorine residual, 3.0 ppm...2 hr on: 2 hr off
Box No. 6—Nominal chlorine residual, 1.5 ppm...2 hr on: 6 hr off
Box No. 7—Nominal chlorine residual, 3.0 ppm...2 hr on: 6 hr off

It should be stated that the chlorine residuals given in the foregoing table were determined colorimetrically by the orthotolidine method with a disk-type comparator, instead of deter-

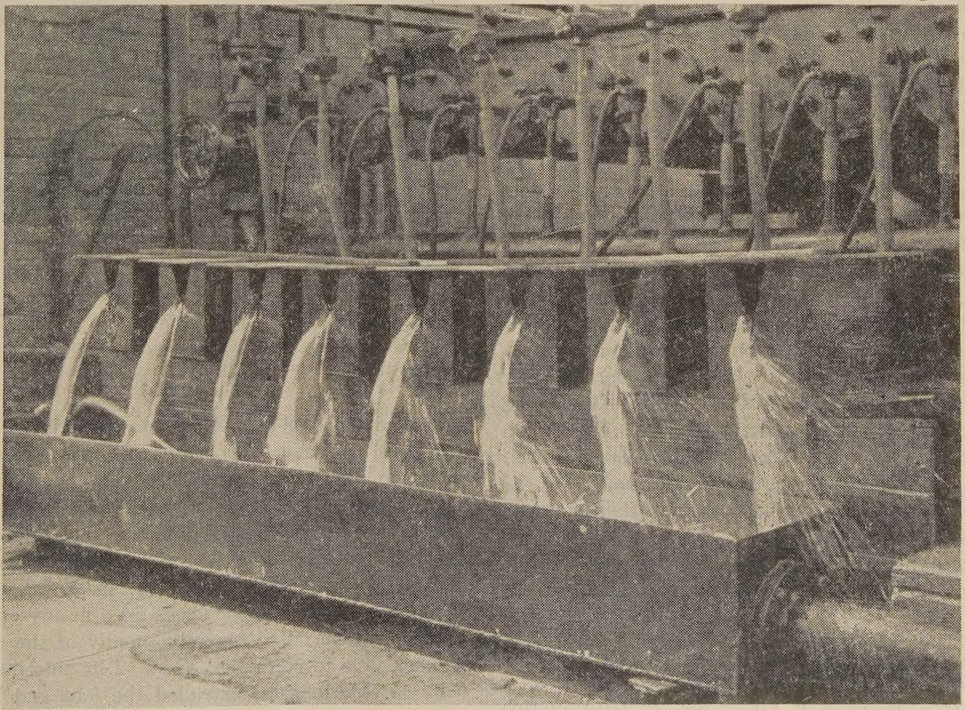

Fig. 8 Arrangement of Equipment Used on Chlorination Studies, Kure Beach, N. C.

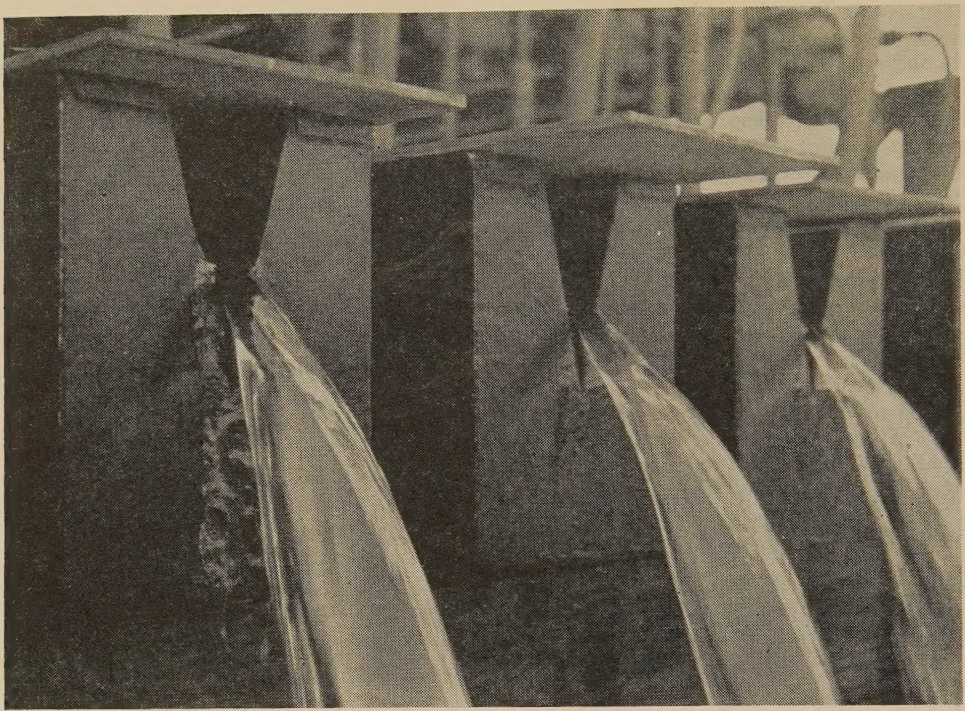

Fig. 9 Close-Up View of Weir Boxes, Chlorination Test Equipment, Kure Beach, Showing Slime at Weir of Box No. 1, Absence of Slime at Others

mined by the starch-iodide method,[4] or by the methyl orange method[5] and accordingly are merely nominal values. It is possible that absolute values in the lower concentrations may have been as much as 100 per cent higher than shown in the tabulation. On the other hand, for comparison with figures secured by the orthotolidine method, of course no correction is required in these tabulated values.

At the end of 24 hr the clusters in the control-weir, box No. 1, with no treatment, were still firmly attached and no noticeable change had taken place. In all of the other weir boxes the mussels had begun to separate from the clusters and many were lying loose on the bottom of the containers with no attachment. At the end of 6 days no change had taken place in the control-weir, box No. 1. The clusters were still firmly attached, and the individuals in an apparently healthy condition. In the containers in weir boxes No. 2 and No. 3, which were being given continuous chlorine treatments with residuals of nominally 0.25 ppm and 0.5 ppm, respectively, the mussels had all lost their holdfasts. The shells of many were opened wide, and when the animal thus exposed was touched with a teasing needle the shells were not closed. The effect on slime-producing organisms from the continuous presence of chlorine in the sea water is shown in Fig. 9, a view of the weirs of boxes No. 1, No. 2, and No. 3, and the absence of mussel activity in water of 0.25-ppm chlorine concentration is shown in Fig. 10. The clusters in weir boxes Nos. 4, 5, 6, and 7 had also severed all attachments, but the majority of the specimens of all sizes had the shells tightly closed. Comparatively few had the shells open.

At this time, the end of 6 days, all of the containers were removed from the weir boxes and were submerged again in clear, untreated, flowing salt water for 24 hr. All of the specimens in control container No. 1 appeared to be alive and in excellent condition. At the end of the 24 hours none of the specimens in containers Nos. 2 and 3 had revived, all shells were widely opened, and disintegration of the animals thus exposed had started. In containers Nos. 4, 5, 6, and 7, all of the specimens were still unattached but many still had the shells tightly closed and only 25 to 50 per cent had the shells open in any of these containers.

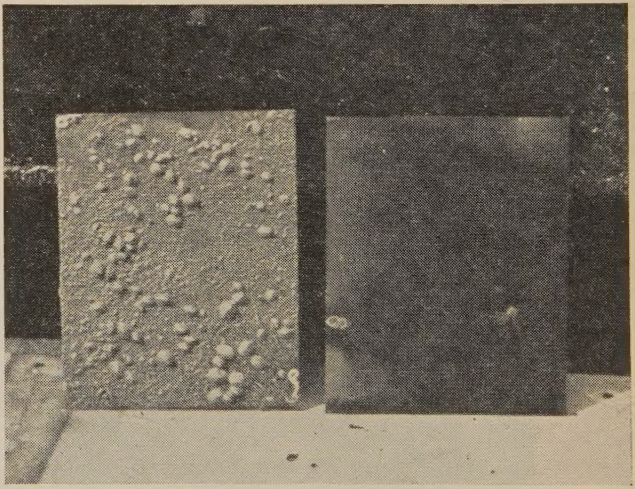

Fig. 10 Glass Panels From Chlorination Test, Kure Beach, Comparing Effects of Continuous 0.25-Ppm Nominal Chlorine Residual and Untreated Sea Water Used for Control

It should be noted here that many of the mussels which remained alive in container No. 6 (2 hr chlorination at 1.5 ppm, 6 hr no chlorination) extruded the foot and began to migrate within a few moments after having been submerged in clean salt water. Within 24 hr these individuals had again formed in two or three clusters and were firmly attached. This to a lesser degree was true in the case of the mussels in containers Nos. 4, 5, and 7. It was also noted that the very young specimens only 1 mm or less in size were as quick to recover and as agile in migrating as the larger specimens. This would tend to discount the belief that the shelled young are necessarily more susceptible to unfavorable conditions than the older individuals. Once this form has been reached the immature *Mytilus* is soon as resistant as the mature specimen. However, it is probable that the free-swimming larvae, without the protection of the shell, would succumb quickly to such severe conditions.

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[4] "Residual Chlorine," Standard Methods for the Examination of Water and Sewage, American Public Health Association, 1936, pp. 164–165, and 228–232.

[5] "Colorimetric Determination of Free Chlorine With Methyl Orange," by Michael Taras, *Analytical Chemistry*, American Chemical Society, vol. 19, 1947, pp. 342–343.

The mussels in containers Nos. 2 and 3 were discarded, and the dead mussels in containers Nos. 4, 5, 6, and 7 were removed and new specimens were added. The tests were then repeated for 5 consecutive weeks, following the same procedure and with approximately the same results. Since a considerable number of new healthy specimens were added to containers Nos. 4, 5, 6, and 7 at each weekly interval, the maximum period of individual survival under the intermittent treatment was not determined.

### SUMMARY OF KURE BEACH TESTS

Continuous chlorination at 0.25 and 0.5 ppm resulted in a complete kill of *Brachydontes exustus.* In addition, no fouling organisms of any kind, or slime film, could be found in these weir boxes.

A varying number, probably averaging 50 per cent, of *Brachydontes exustus* were killed in the weir boxes which were provided with intermittent chlorination. In addition, living barnacles and Bryozoa were found in these weir boxes.

### RELATED OBSERVATIONS AND DEDUCTIONS

Some organisms, generally those which are not provided with a protective shell or covering, are much more susceptible to unfavorable conditions than others. Among such organisms the sea anemones and hydroids probably belong. It is of importance in this connection to note that blocks of wood which were placed in the control weir box at Kure Beach Station were destroyed by teredo in a few weeks. Similar blocks placed in all of the other weir boxes showed no trace of any borer attack. It is evident that the embryonic teredo without the benefit of any shell for providing protection is unable to survive any of the chlorine dosages used during this test. On the other hand, once having succeeded in entering the wood, the mature form of teredo would be well protected against all but the most severe unfavorable conditions.

Those marine mollusks which are accustomed to living exposed in the between-tide area are frequently provided not only with strong shells which can be closed very tightly, but also with very powerful muscles which enable the animals to keep the shells tightly closed for long periods of time. The scallops and mussels are of this type while the various species of burrowing soft clams, which are protected by the burrows they live in, frequently do not have tightly fitting shells or strong muscles for closing them.

The mussels living on our tidal flats are out of water and exposed to the rays of the hot sun during the summer for 2 hr or more during each low-tide period. For them to survive, it would be essential that they protect themselves by keeping the shells tightly closed during the period of exposure. It would appear to be a necessary adaptation. It would seem probable that the *Mytilus*, which can remain closed and survive exposure to the air and hot sun for 2 hr each day, could survive equivalent unfavorable conditions in an intake tunnel for equal periods of time.

It would seem from the tests described that continuously but comparatively slightly unfavorable conditions would eliminate the undeveloped and unprotected embryos of the fouling marine organisms. This would be the most desirable objective to attain. It would also seem that much more unfavorable conditions are necessary to produce a kill when the organisms have passed from the embryonic stage to the mature form.

On the other hand, the evidence seems to indicate that, with some *Mytilus*, even slight and intermittent chlorination would result in the mature specimens releasing the holdfasts. In this way it is conceivable that, if still small, they might then be carried through the system without causing further trouble. However, it is also possible that with sufficiently low velocities this might result in an accumulation on the bottom of the tunnel which, eventually, would have to be removed.

### ACKNOWLEDGMENT

The author desires to express his appreciation to Mr. Frank L. LaQue of The International Nickel Company, for permission to reproduce the illustrations of test equipment used at Kure Beach Station, and to quote from results secured.

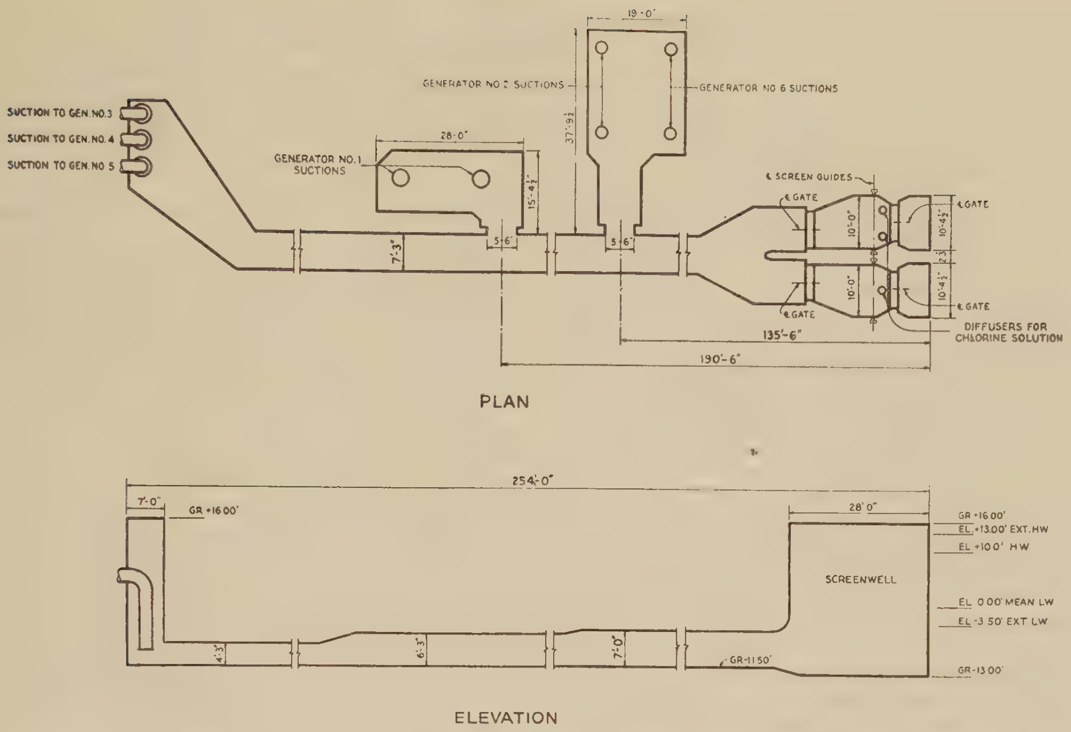

Fig. 1 Arrangement of Intake Tunnel, Electric Generating Station

# Project Study for the Mitigation of Marine Fouling

By I. A. PATTEN,[1] LYNN, MASS.

**The growth of marine organisms with resultant fouling of aquatic vessels and tunnel structures, throughout the years, has presented the utility engineers with a problem the effect of which creates lower efficiencies and higher maintenance costs. Mitigation of such growth and fouling on several occasions has been studied by industrial engineers and biologists. The result of such studies indicates *Mytilus* are the most difficult to control. The paper is a résumé of experiments and the development of a chlorine program which to date has proved effective and economical.**

## Intake-Tunnel Arrangement

In the year 1927, fully realizing the necessity of expansion to meet the future supply of electricity, the Lynn Gas & Electric Company, Lynn, Mass., entered into a construction program the ultimate objective of which was to provide an additional 60,000-kw capacity. This entire development was to be housed in a new structure adjacent to the old generating station.

Included in the new development was a reinforced-concrete intake water tunnel for condenser-cooling purposes. The tunnel as designed provided for one concrete rectangular tube, 7 ft square near the intake and of progressively decreasing cross section, approximately 250 ft in length, as shown in Fig. 1. The intake end on the Lynn Harbor front, submerged to minus 13 ft relative to mean low-water datum, is equipped with inner and outer gates which permit unwatering and cleaning either screen well without interruption of service. The new tunnel, however, is a single-tube conduit; consequently, when tunnel cleaning becomes necessary, it can be accomplished only by shutting down the main tunnel and employing inadequate by-pass connections for circulating-water requirements. The maximum demand for total cooling water at this station is in the order of 9400 cfm. Due to the design and location of the suction chambers in the tunnel, the velocity of the water varies in its flow, but for all practical purposes the maximum rate is around 3 fps.

## Early Fouling Problems—Equipment Outages

The new station was put into operation in the fall of 1929, and, following approximately a year of satisfactory operation, condenser fouling due primarily to mussel and marine growths occurred. Within a relatively short time condenser outages were becoming very frequent, thus necessitating search for the cause of this trouble. A diver was sent into the tunnel to determine the marine-growth condition existing therein, and much to

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[1] Superintendent, Lynn Gas & Electric Company.

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Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors, and not those of the Society. Paper No. 49—S-20.

the surprise of all concerned, a very heavy congestion of *Mytilus* (common mussels), *Tubularia* (sea moss), and *Metridia* (sea anemone) was found. These growths were firmly attached to the walls and roof of the tunnel and varied in amounts fairly consistent with the rate of flow; that is to say, the nearer to the intake, the more plentiful the attachment of the wall surfaces.

Now the handwriting was on the wall, so to speak, the operational problem of "condenser fouling" had a brother—"tunnel congestion," and these two factors were of grave concern as time passed.

It was a frequent occurrence for each turbine generator to be out once a week for condenser cleaning, and the deposits of slime, silt, and mussels in the tubes were very disheartening. The economics of such conditions in a modern generating station were embarrassing as outages necessitated purchasing power from a nearby utility, and operating efficiency was far below normal, primarily due to poor vacuum conditions in the turbine units.

### Manual Removal of Fouling Costly

In the spring of 1931 it became necessary to unwater the tunnel and to do a thorough cleaning job, which was termed at the time the "clamming" expedition. This resulted in the removal of approximately 160 tons of mussels and other marine growths. Accompanying the marine growth, there was an accumulation on the floor of the tunnel to a depth of 18 to 24 in. of harbor silt, mussel excretion, and many dead-mussel shells.

From Fig. 1 it is obvious that an undertaking of this kind was costly and difficult to perform, as all debris must be raised from the tunnel through four manholes throughout the length. The temporary suction line was attached to the station's largest turbine generator (25,000 kva) and the deficiency of kilowatts was supplied from an adjacent system. The time consumed was approximately 20 hr, and the cost in the vicinity of $6000 for equipment and labor. Yet, a tunnel-cleaning program had to be established for at least once every 12 months. The reality of this problem, plus the headache of condenser cleaning, the loss of station efficiency, and the accompanying high operating maintenance cost were factors which led to vigorous study and investigation of the mitigation of marine growth by means of agents not then too familiar to the utility industry.

### Initial Investigation and Observations

The investigation was begun by correspondence with other utility companies and a few industrial plants to gain knowledge of their experience. In a few cases, chlorine was mentioned favorably even though very little information was available that could be applied directly to the complete elimination of mussels by chlorination. The Department of Commerce, Bureau of Fisheries in Washington, supplied information relative to the spawning of mussels which they stated should cease about the first of August but added the cautionary comment that the free-floating larvae would exist in abundance for at least 2 weeks after the end of the spawning season and might be expected to attach themselves within the intake system during such period. They also advised that the use of chlorine gas for preventing the growth of mussels was being investigated by the Bureau.

During the interim two interesting facts were learned. The first was that the Atlantic seaboard during the seasons of 1930 and 1931, had produced what was termed in those days abnormal mussel years. While it seemed within reasonable prospect that future years would be more favorable, there still also seemed sufficient room for pessimistic doubt to warrant continuance of the investigation. The other, which was felt in part directly responsible for the mussel conditions in the immediate area, was the changed sea-water condition in Lynn harbor. Up to 1929 the Lynn sewerage system had been flowing directly into the harbor, resulting in a fairly high concentration of pollution in the water. Subsequent to 1929 an outfall sewer system was laid, and the sewerage pollution was removed from the harbor waters, which was favorable to marine growth.

### Initial Trial of Chlorination

Further study, including reference of the problem to our engineers and to one of the country's most noted marine biologists, led to a decision to try chlorine as a preventive against mussel development. The equipment then available was not too elaborate or complete, and the installation and operation were equally in question as this process was still in its infancy. However, a voluntary committee was formed and, securing what equipment there was available, an operating schedule was set up on February 23, 1931. The recommended and trial cycle of operation consisted of $7^1/_2$ to 15-min injections once every 3 hr with a chlorine residual 0.4 to 0.8 ppm.

After a few months of operation there was found to be little if any improvement in the mussel situation. This, coupled with the fact that corrosion-erosion of condenser tubes and graphitization of condenser water boxes were noticed about the same time, aroused serious doubt as to the advisability of continuing chlorination. However, persistency prevailed and, in our endeavor to overcome these corrosion conditions, zinc plates were installed in the water boxes, ferrule extensions applied at inlet ends of condenser tubes, and the water-box surfaces treated with hot Apexior.

While these measures offered relief, it was apparent that they should be termed at best deterrents rather than cure. Chlorination was continued until May, 1932, and then discontinued, as everyone felt the objective, mussel mitigation, had not been reached and its attainment uncertain. While all felt chlorine had not failed completely, its continued use seemed unjustifiable until many of the unknown factors had been given further study and evaluation.

### Corrosion not Caused by Chlorination

Subsequent to discontinuing chlorination, the following became apparent:

1 The corrosion-erosion within the condenser tubes was being caused primarily by free oxygen in the circulating water, and the same cause seemed the primary factor in the attack on the ferrules, tube sheets, and water boxes. Tests showed that a considerable amount of entrapped air existed in our intake tunnel. This air, when passing through the circulating pumps and thence into the condenser, resulted in the liberation of large quantities of free oxygen. The first preventive step was to install a vent standpipe about midway of the intake tunnel. This procedure immediately showed favorable effects and was followed by installing air erosion eliminators in the condenser water boxes, in addition to the vent.

2 Stray-current electrolysis was also an important factor in the observed corrosion. In the process of investigation, tests were conducted for electrolytic action which discovered evidence of stray currents prevailing not only upon the condensers but the pump impellers and associated equipment. Preventive measures were taken, and it was soon learned that the foreign current extended out into the screen well and forebay. Finally, an open negative was discovered on an adjacent direct-current system ground submerged in the Saugus River. When repair to the negative was effected, the electrolytic condition was eliminated. These facts are mentioned to indicate how our thinking changed with reference to the effect of chlorine on this type of equipment

### ELECTROCUTION ATTEMPTED

One other experiment, worthy of mention in passing, was an attempt to electrocute various types of marine growth. Two framed wire grids were submerged in the forebay several feet outside the screen well. Low-voltage electric current was supplied to one grid and no energy to the other. The grids were withdrawn monthly for examination. The energized grid contained few if any mussels, and other types of marine growth, such as barnacles, etc. On the unenergized grid quantities of mussels and other marine growth were present. It seemed probable at the time that electric energy supplied through a properly designed screen or grid system of some kind would result in killing the mussels when in the embryonic or larval stage. However, due to lack of available equipment, after about 5 months of operation, the experiment was discontinued without actually determining the merit of the scheme.

### DECISION TO RESUME CHLORINATION

From 1932 to 1944 little was accomplished in mussel mitigation, and the tunnel cleaning continued once each year. The season for cleaning was changed from spring to fall, however, and fall cleaning proved much more satisfactory than spring cleaning, that is, the tunnel was cleaned after the fall spawning season, say, in October, consequently eliminating a large proportion, by volume at least, of the mussels by not permitting them to remain in the tunnel and develop during the winter months. The majority of mussels then to be removed, consisting primarily of the current summer's breeding, were much smaller in size.

These last 10 years or so the clamming business was becoming tiresome, especially without a market for the product but, with renewed hope from several biologists, another vigorous attack was begun on the investigation and control of marine growth.

In June, 1945, thorough study for the elimination of marine growth, *Mytilus* especially, was resumed. All phases of the intake-tunnel conditions and condenser operations, all tests, and previous experiments were reviewed and analyzed. Several of the previous experiments were found inconclusive in the light of development and research through the intervening years, and a new tentative program finally was agreed on. Chlorination was decided upon as the weapon, and the greatest problem was the cycle of operation; intermittent chlorination with high residual, or continuous chlorination with much less residual. The burden of opinion from our consultants was in favor of intermittent chlorination. Accordingly it was decided again to try chlorine with intermittent injection. The installation of needed equipment was completed in November, 1945.

### FOULING TEST PANELS

About this same time an investigation was undertaken to secure information on the current natural rate of marine fouling by the aid of a series of test panel boards, each 6 in. × 12 in. and $^1/_8$ in. thick of black plastic composition, five of which were continuously active. The test panels were submerged within 3 ft of the bottom of the forebay and 5 ft in front of the intake tunnel at the rear of the screen house. Four of the test panels in use were given numerical identifications and the fifth serving as a control was designated *X*.

After the submersion of the test panels for 1 week, one of the numbered panels and the *X* control were removed and immediately wrapped with care in paper towels and sent to the biological laboratory for analysis. This was done on Monday of each succeeding week. A data sheet accompanying the panels listed tidal condition, sea-water temperature, and location from which the test panels were removed. After the first month, each numbered test panel should give a sample representative of potential fouling development in the previous 4 weeks for comparison with the latest single week's record of the *X*-control panel.

Later in 1946 a test station was added about mid-length of the tunnel, directly in the flow of the chlorinated sea water to indicate the chlorination results. Test panels of different types of material including clear lucite and reinforced cement were tried, and Plexiglas supporting rods in place of flexible supporting cables. Widely varying results obtained from these panels led to the conclusion that they were not giving dependable indication of tunnel-fouling conditions.

### CHLORINATION RESUMED

On November 3, 1945, the intake tunnel had been thoroughly cleaned. Chlorination on hand control was started November 4, 1945. Under this first schedule, from November, 1945, to April 3, 1946, chlorine was injected 1 hr, twice daily at 0.2 ppm residual. On April 3, 1946, time-clock automatic control was installed, and the chlorine-injection cycle was changed to 30 min each 8 hr with residual at 1 ppm. After 1 month of operation on this program, it was decided to increase the residual to 2 ppm and this was continued until about October 1, 1946.

On October 24, 1946, with approximately 1 year of experience with chlorination, the tunnel was inspected by a referee committee and subsequently cleaned. As compared with previous years, approximately as many mussels in number were found, but the average size was considerably smaller. The belief of all present was that, while chlorine had been instrumental in limiting the growth, it apparently had in no way affected the number present and adherence of the mussels to the walls of the tunnel. *Tubularia* and *Metridia*, on the other hand, had decreased materially.

Definite information was not available on how long a mussel can exist with the shell completely closed, without oxygen. Our biological consultants expressed belief that such a condition might prevail for many hours, and recommended longer periods of chlorination at lower residuals. This raised the question that if the length of the chlorine-injection period was increased sufficiently, what was the minimum residual concentration at which mussels could be killed.

From operating experiences and indecisions, the committee again conferred to determine whether or not sufficient improvement had been gained to warrant further experimental work and retention of the chlorinating equipment. From this conference the following was agreed:

1 Chlorination had brought no adverse results on condenser tubes, water boxes, or pump impellers.

2 *Tubularia* and *Metridia* had been practically eliminated from the tunnel, screen well, and suction chambers.

Even though the mussels were as numerous, they were smaller in size and apparently not so firmly attached to the surfaces. The chlorine plant had operated efficiently and satisfactorily. Thus, weighing the results, decision was reached to continue for another 12-month period. It seemed beyond doubt that by so doing operations would be improved, and the economics would justify chlorination, as materially better vacuum was then being secured owing to cleaner condenser tubes and less fouling of condensers.

### PILOT TUNNEL

During the winter of 1946–1947 further efforts were made to determine the seasonal changes which should be made in the chlorination schedules to compensate for changes in water temperature and spawning season. System-load conditions prevented frequent inspections of the main tunnel. This, together with the misleading indications given by test panels, prompted

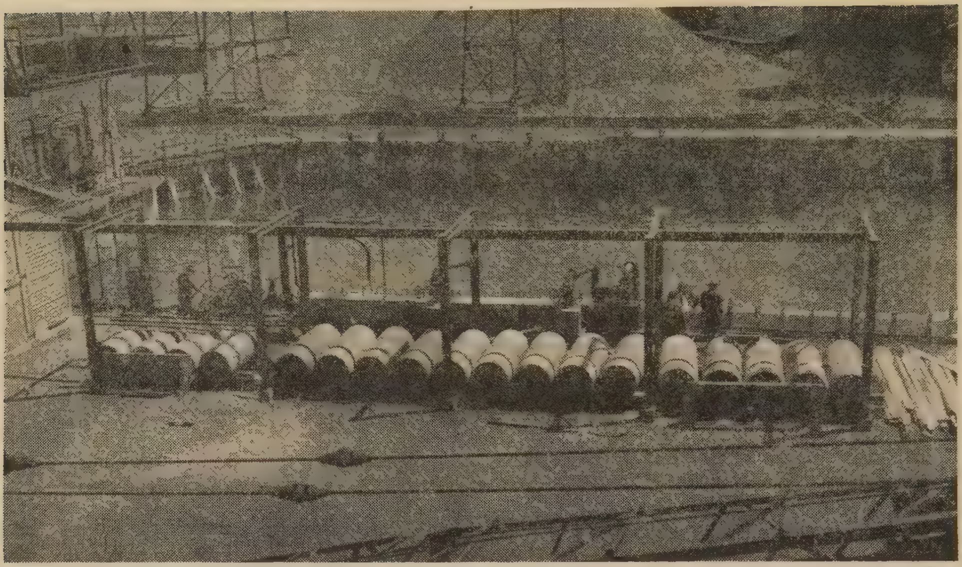


Fig. 2 Pilot Tunnel at Intake Slip

the construction of a miniature tunnel which would allow as frequent inspections as desired. The pilot tunnel, which is shown in Fig. 2, is an exact reproduction of the main tunnel constructed on a scale of 1 to 7. Overflow ports of identical shape and proportions simulate entrances to the suction chambers of the various machines in the main tunnel. Water from the forebay is pumped through the pilot tunnel continuously, and chlorine is diffused at the same proportionate rate as used in the intake tunnel. In other words, chlorinating programs for the main and pilot tunnels are identical. Removable covers were installed at the top and end of the pilot tunnel, providing for intermittent inspection of inner surfaces of the tunnel.

In June, 1947, water was fed initially through the pilot tunnel and, from its subsequent inspections, establishment of more definite ideas relative to chlorination cycles and residuals became possible. In the section of the tunnel nearest the intake, which was designed to operate without chlorine injection, mass distribution of the mussels was obviously in inverse relation to local velocities, much as observed in the intake wells of the main tunnel. When chlorination was started in the pilot tunnel there had accumulated in the wooden discharge trough a considerable growth of sea moss and marine organisms which disappeared within a few days after chlorination.

### Plankton Net

Coincident with operation of the pilot tunnel, an attempt was made to employ the Plankton net for trapping live organisms, the trapping equipment used consisting essentially of a closely woven silk sleeve of conical shape with a 6-in. opening at the entrance and a $1^1/_2$-in. opening at the other end to which a sampling bottle is attached. Results were unsatisfactory even with the aid of a metal frame and rudder to hold the net submerged and parallel to the water flow. Very few mussels were trapped, although more numerously present as evidenced by infection of the pilot tunnel 20 ft away. No doubt the difficulty was due to the low velocity of flow in the forebay as such equipment has been effectively used at higher velocities.

### Thermal Treatment

Early in 1947 consideration was given to temperature treatment by steam or hot water for mussel elimination. The conclusion reached was that the procedure could be made effective and, in some instances, possibly economical but, with the single main intake tunnel and the system demands, it was impractical for Lynn Station. Consequently the idea was abandoned.

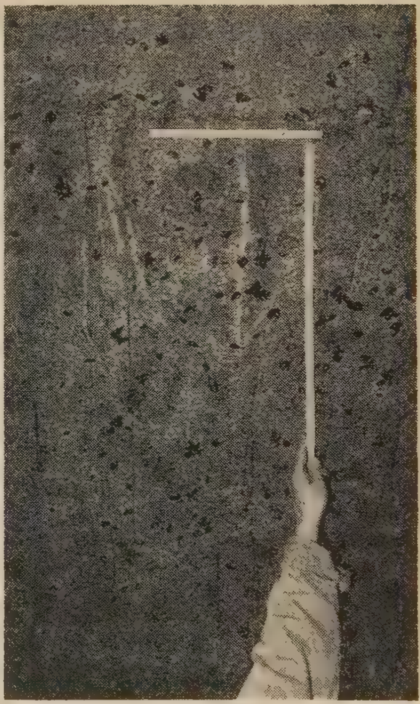


Fig. 3 East Side Wall of Tunnel, July 20, 1947

### Intermittent Chlorination Continued

On June 8 and on July 20, 1947, the main tunnel again was inspected by the referee committee and in comparison with inspections of October and November, 1946, a considerable area of concrete surface was visible, and the small clusters of mussels were scattered as shown in Fig. 3, taken on July 20, 1947. This was encouraging, as the previous inspections in the fall of 1946 showed continuous blanket formations from 2 in. to 4 in. thick on the walls as shown in Fig. 4 taken November 16, 1946. For

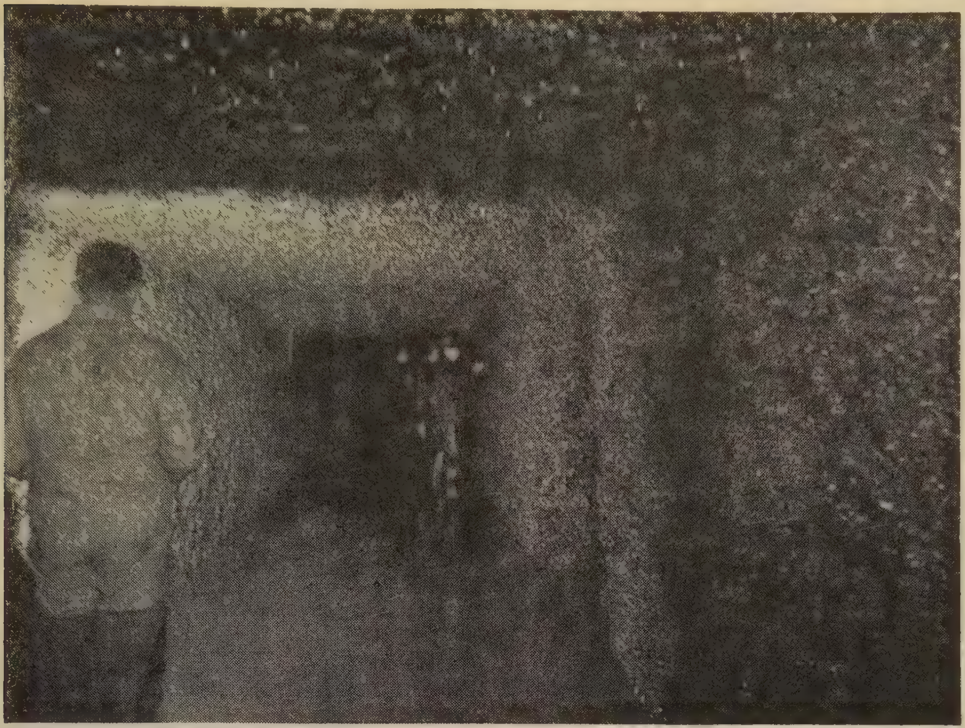


Fig. 4 General View in Tunnel, November 16, 1946
(Courtesy of Woods Hole Oceanographic Institution.)

future inspection comparisons, all metal and tunnel surfaces were zoned and their observed conditions recorded.

Questions raised from this 1947 inspection were as follows:

1 Why are certain areas free from mussels and other areas infested in such varying degrees?

2 Were chlorine diffusion nozzles designed properly to prevent streamlining of chlorine?

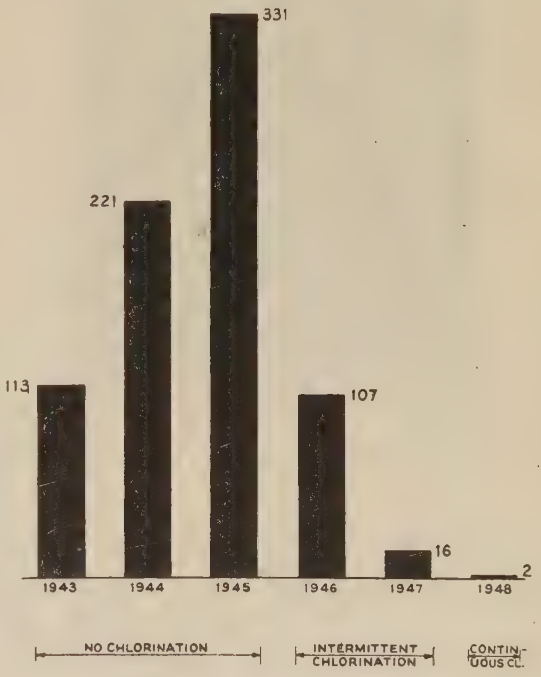
3 Due to irregularity in surface areas in concrete, did "water slip" lower chlorine concentration on the wall surface?

4 Are the survivors the "supermen" of the mussel family or is our chlorine program improperly designed?

These questions among others have been studied by H. E. White.[2]

Continuing the tests and tunnel examinations during the summer months of 1947, it was naturally gratifying when the November cleaning produced only 16 tons, compared with 107 tons in 1946, and 331 tons during 1945, as shown in Fig. 5. However, complete control was the goal sought, and anything short was not considered satisfactory; consequently, chlorination was continued during the winter of 1947–1948, on the basis of 30 min each 8 hr at 0.75 ppm residual.

November, 1947, being the second anniversary of the chlorine equipment, the question of its continued use had again been considered. Favorable factors included progress in mussel control, no further signs of corrosion-erosion of condenser and related equipment, reduced maintenance costs for condenser fouling, and cost for chlorine consumption had not exceeded the estimate. The single unfavorable factor was lack of full mussel control. The decision again was favorable for retaining the chlorination equipment.



NOTE: 1948 ESTIMATED FROM VISUAL INSPECTION

Fig. 5 Tons of Mussels Removed Annually From Intake Tunnel

On April 25, 1948, tunnel conditions were found about comparable with November, 1947, after cleaning. The few mussels present were small, ranging in size from 1 to 5 mm at approximately 2 to 5 per sq ft of area, even though chlorine injections were only three 20-min periods each 24 hr at 0.75 ppm residuals. On the other hand, elimination of mussels was not complete.

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[2] "Control of Marine Fouling in Sea-Water Conduits Including Exploratory Tests on Killing Shelled Mussels," by H. E. White, published in this issue of the Transactions, pp. 117–126.

Decision was in favor of continuous chlorination at 1 ppm residual which was at once put into effect.

### CONTINUOUS CHLORINATION

On June 27, 1948, after tunnel inspection which showed favorable results, a program of continuous chlorination at 0.5 ppm residual was set for the balance of the 1948 recognized propagating season, or until water temperatures dropped to 40 F, unless future inspections of the pilot tunnel indicated the necessity for change. Immediately after the inspection, new dual diffusion pipes were installed in one screen well at the tunnel intake, and apparently they are a decided improvement over the single diffuser.

The main tunnel was opened approximately each 6 weeks for the balance of the season, and results continued satisfactory. As shown in Fig. 6, the last seasonal inspection was made on October 17, 1948. All of the referee committee present agreed that a decided improvement existed. Mussels where present were, in general, widely scattered, many wall areas completely void of any marine growth, mussels present were of miniature dimensions—some very small yet with completely formed shell. Attachment to the walls was rather weak with, it seemed, fewer byssus threads, while on the floor almost all the mussels were dead. From visual summation it was estimated, if the tunnel was thoroughly cleaned, the maximum in weight of all types of marine growth and silt would not exceed 2 tons, largely concentrated in the relatively less active north end of the tunnel where chlorination had not been continuous. Because of this small extent of the fouling, we decided not to clean the tunnel.

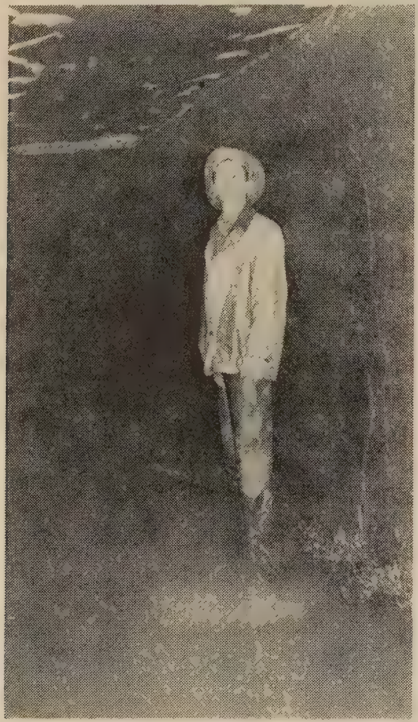

FIG. 6 EAST WALL OF INTAKE TUNNEL NEAR INLET, OCTOBER 17, 1948, SHOWING BARE CONCRETE AFTER FULL SEASON OF OPERATION

The view of the tunnel interior given in Fig. 6 is representative of the east side wall in the continuously active zone, photographed October 17, 1948. The man is standing in 3 to 4 in. of water about 20 ft from the inlet end of the 7-ft-square section of the tunnel. Grouping of large mussels is visible only near the base of the wall. The remainder of the wall and roof in this vicinity is devoid of any fouling.

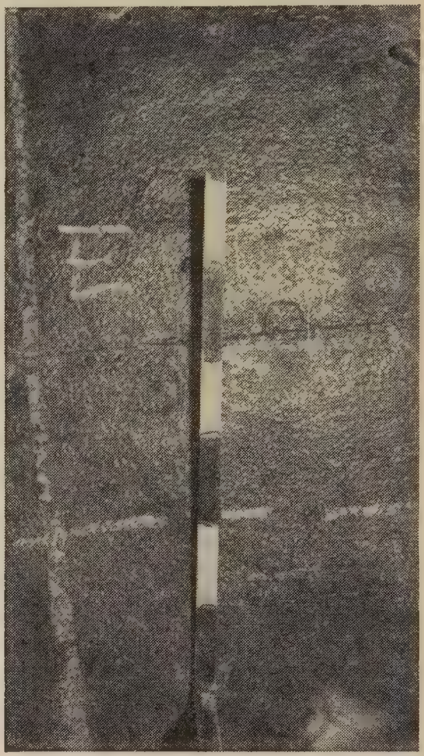

FIG. 7 CLOSE-UP OF EAST WALL, MID-LENGTH OF INTAKE TUNNEL, OCTOBER 17, 1948
(Black and white scale divisions approximately 1 in.)

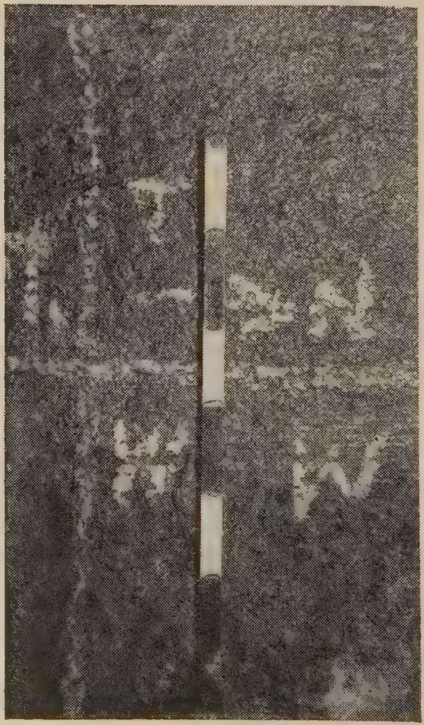

FIG. 8 CLOSE-UP OF WEST WALL, MID-LENGTH OF INTAKE TUNNEL, OCTOBER 17, 1948
(Black and white scale divisions approximately 1 in.)

Figs. 7 and 8 show at close range views typical of the general area of the east and west walls, respectively, about 110–120 ft further from the inlet end of the tunnel where mussels were found in numbers of 1 and 11 per sq ft. Chlorine effectiveness observed in the main tunnel was reproduced closely in the pilot tunnel where walls in contact with chlorinated water were almost completely free from fouling attachment. Contrast of areas respectively ahead of and following the point of chlorine introduction in the pilot tunnel is rather strikingly brought out in Figs. 9 and 10, views of the interior taken on October 20, 1948.

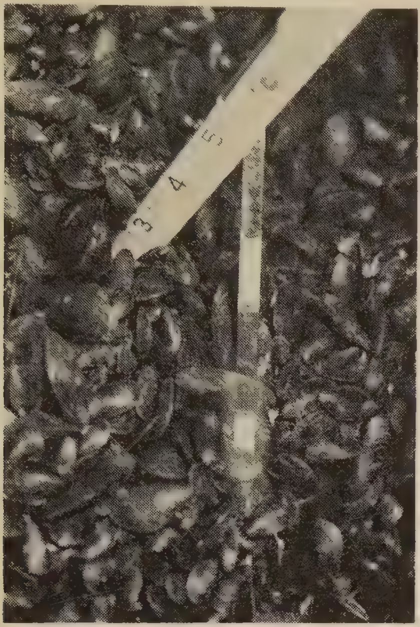

Fig. 9 Close-Up of Matted Mussels Inside Pilot Tunnel—Natural Conditions Ahead of Chlorine Injection, October 20, 1948, After One Fouling Season

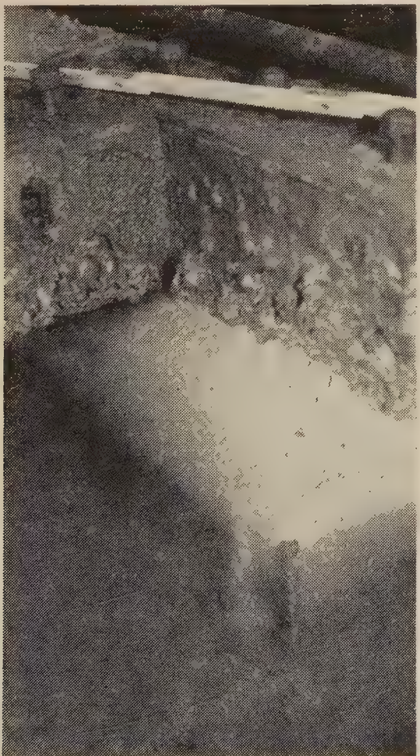

Fig. 10 Clean Concrete Wall of Pilot Tunnel Beyond Chlorine Injection, October 20, 1948, After One Fouling Season

## Suggestions

From the experience at Lynn Electric Generating Station the following suggestions are offered to those who have or are anticipating marine-growth control in forebays, tunnels, suction pipes, or other aquatic structures:

1 Acquire thorough familiarity to the last detail on items such as water analysis and water temperatures, especially during seasonal changes.

2 Determine as accurately as possible the hydraulic conditions and variants, including velocities in the structures in question.

3 Determine as accurately as possible the metallography of all equipment in the plant through which this water will pass.

4 Study as accurately as possible the amount of expenditure created directly by marine fouling in the plant equipment. There is now sufficient information available which at least will give a fair indication of the cost of elimination. In turn, this should establish wherein the economics of the problem lies.

5 Do not be impatient. Remember that the price of success is eternal vigilance, and problems not too readily solved are always to be expected.

## Conclusions

In conclusion, the following are believed factual to at least the present degree of success attained at the Lynn plant:

1 Chlorine to the extent and magnitude of actual usage has not caused deterioration of condenser tubes, water boxes, pump impellers, or associated equipment although condenser tubes are of various alloys and makes.

2 Even in the days when success of marine-growth elimination by chlorine seemed doubtful, benefits were realized due to elimination of slime film on condenser tubes, which resulted in better vacuum and saving in the coal pile.

3 As the trial programs have progressed there have been direct and appreciable savings in labor for condenser cleaning, readily evaluated.

4 For the year 1948, what can be safely termed operating savings, which consist of avoiding the intake-tunnel cleaning, fewer condenser outages and cleanings, higher vacuum with a resultant reduction in coal usage, have been summarized, giving estimated gross operating savings of $20,000. Deducting from this the gross operating cost of the chlorine plant, the direct cost for chlorine purchases, interest, taxes, and depreciation on the chlorine plant, the estimated net saving for the year is about $12,000. It will be noted this estimate has been made on a conservative basis, applying only the recognized and tangible savings, and not including other variables which might be included by thorough analysis.

The author wishes to express his appreciation to Dr. William F. Clapp, his assistant Mr. Peter Richards, Dr. Louis W. Hutchins of Woods Hole Oceanographic Institution, Messrs. R. B. Martin and S. H. Newland of Wallace & Tiernan, and Messrs. E. B. Powell and H. E. White of Stone & Webster Engineering Corporation. Without their able assistance and determination we could not have succeeded to the present degree of mussel and marine-fouling control. While we shall continue to strive for perfection, even though we fall short, we feel assured that satisfactory operations can be continued and with a reasonable degree of economic success.

# Control of Marine Fouling in Sea-Water Conduits Including Exploratory Tests on Killing Shelled Mussels

By H. E. WHITE,[1] BOSTON, MASS.

**Hundreds of tons of mussels may accumulate in the circulating-water tunnels of a large seaboard power station in a single season. Explicit practical procedures have been determined for meeting this problem by complete extermination of fully shelled mussels by chemical treatment, moderate temperature elevation, or combination of both. General results have broad application. Exploratory tests have demonstrated great practical influence of very moderate changes in temperature of the sea water in extermination of mussels. Any elevation of temperature reduces the required consumption of chlorine, which has been the usual killing agent. For plants with suitable arrangements and load conditions, it appears practical to achieve positive control of marine fouling in tunnels without chlorine or other chemicals by periodic increase of sea-water temperature to not more than 95 F for northeast coastal plants. Numerical results of various treatments as observed in the exploratory tests are summarized by charts.**

### CONDITIONS WHICH LED TO PROJECT

MARINE fouling develops at such a rate at some coastal sites that it can become a major factor in design of the circulating-water system of a steam-electric power station. In the absence of suitable control treatment, hundreds of tons of mussels may accumulate in the tunnel system of a large power station in a single season. Similar conditions arise in connection with sea-water systems of industrial plants. Even where some degree of control has been employed, accumulations of mussels have reached serious proportions. In some cases complete plant shutdowns have been required periodically for scraping and digging out mussels by hand labor.

With high plant investment and heavy demands for output and continuity of power supply, shutdowns for cleaning tunnels become increasingly objectionable. Continuous 100 per cent cleanliness of tunnels is desired in some plants to avoid periodic cleaning, though the normal intervals between cleanings may be several years. This view is prominent particularly (1) where tunnels are long, (2) where access is difficult, and (3) where labor conditions are unfavorable.

### OBJECTIVES OF STUDIES

The objectives of the present project were to determine, if feasible, a practical procedure for control of marine fouling which would give full assurance of 100 per cent extermination at will, under severe conditions with minimum chlorine consumption, and also, to determine the limitations of control treatments. Divergent opinion on questions of detail left no alternative but to make detailed observations. The specific objective, therefore, was to determine practical procedures which would give positive control of marine fouling based on more specific quantitative observations of actual results of treatments than had been available.

### SCOPE OF INVESTIGATION

This paper relates particularly to control of marine fouling where sea water is used for cooling purposes. The primary emphasis is placed on extermination of shelled mussels because, as discussed later, these mussels are commonly the most troublesome element of fouling in circulating-water tunnels of power stations along the East Coast. Somewhat similar conditions are found on the West Coast. Results were needed as soon as possible; hence, although refined methods of tests were laid out, lack of time prevented adoption of most of these in the exploratory tests. The test procedures adopted are believed, nevertheless, to be adequate for the immediate engineering purposes.

### OBSERVATIONS IN OPERATING PLANTS

In order to take full advantage of existing experience, personal inspections were made of circulating-water systems of power stations on the East Coast where fouling control treatments were in use, and results appeared reasonably satisfactory. Chlorination exclusively had been used at these stations. Continuous chlorination had been used in a few stations, but all tunnels which were available for internal inspection had been treated by intermittent chlorination.

While treatment had brought great improvement in all cases examined, nevertheless, in the tunnels which could be inspected visually, shelled mussels were found in various quantities regardless of the treatment, even where control treatment was applied conscientiously. In some cases, mussels reached $1^1/_2$ in. in length. At a southern plant which had reported most successful control of mussels, it developed that the so-called "mussel" was an entirely different organism, which was much less resistant to killing treatments.

Fouling growths were removed by periodic manual cleaning. At one of the stations, fouling in the circulating-water tunnel had become so objectionable to the men who were to clean it that serious labor trouble was barely averted.

Various contingencies were found to occur which would permit mussels to enter and make attachment within the tunnels, for example:

Commercial shortage of chlorine temporarily interrupting chlorination.

Mechanical damage to chlorination equipment or piping, due to accident or unusual conditions such as a hurricane.

Deterioration of screens at the inlet of the circulating-water system from corrosion.

Wear of traveling-screen chains, resulting in sufficiently large openings between panels to permit passage of shelled mussels.

In all tunnels inspected, mussels were observed to attach in

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[1] Mechanical Engineer, Stone & Webster Engineering Corporation. Mem. ASME.

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—S-12.

greater numbers in corners between side walls and floor and roof, and in corners following a sudden enlargement of the cross section of the waterway. Any crevices or cracks in the flat surfaces afforded anchorage for mussels even where neighboring smooth surfaces of the wall were entirely free of mussels.

In the course of the investigation special equipment and technique were developed for sampling the sea water at a roof corner of the straight run of a main tunnel during normal commercial operation, in order to determine the reason for accumulation of mussels in corners. Prompt determination of residual chlorine showed full concentration at this location, even with intermittent chlorination, whenever chlorine was being fed. This suggested that the conformation of walls at the corners was more favorable for secure attachment of the mussels.

Another observation which seems of general application was that mussels occur in various arrangements: (1) In the absence of control treatment, all mussels are closely spaced. (2) If diffusion of chlorine is not uniform, localized accumulations occur. (3) Where control is partially effective, arrangements of mussels on the walls, generally develop in the following sequence after cleaning: initially, as individual scattered mussels; then, small groups; later, larger clusters; and, finally, continuous mats of mussels. Continuous mats of mussels may grow to a thickness of about 6 in. before tearing away from the wall and falling to the floor. The process is repeated and more fall to the floor. There they may form a stationary obstruction to the flowing water until removed manually.

Adhesion of clusters of mussels to the walls, in one instance, was found so strong that it was barely possible to pull them off with the fingers without use of metal scrapers. Under such conditions it seemed improbable that a brief application of any water velocity commonly used in a power-station tunnel would detach the mussels. The individual threads secreted by the mussels for attachment are comparatively strong, but the effective strength of the attachment of a cluster results from the great number of interconnected threads used by the group.

In most stations the object of fouling-control treatment was to kill the mussels when very young and most vulnerable, before they had developed shells. Tremendous numbers of these tiny young mussels, only a few hundredths of an inch in length, enter through the meshes of the usual screens during the summer season. Small shelled mussels would pass readily through the screens also. With the usual intermittent chlorination, attachment could be made between treatments.

Although the usual methods for fouling control resulted in great improvement, it was not apparent that any treatment in use in the stations where intake tunnels were inspected, could be relied upon to kill mussels with fully developed shells. Methods which appeared reasonably satisfactory at one site appeared inadequate when applied under other conditions.

From the observations of the survey it was concluded that where 100 per cent cleanliness is required under the ordinary conditions of practical operation, methods of control must be used which would kill shelled mussels and provide satisfactorily for their removal from the system.

## General Test Program

As correlation of field observations was not clear, it appeared that possibly some factors had not been evaluated fully. Uncertainties in attempting to apply results of the plant inspections to conditions at new sites, where full reliability and 100 per cent killing were desired, seemed to necessitate more detailed observations to answer conclusively immediate and essential questions. Tests on full-size circulating-water systems were of course desirable but were impractical at the time, not only from the viewpoint of attendance and expense involved, but also because the extensive trial of new methods in commercial plants involved risk of more frequent shutdowns for cleaning. Therefore the possibility of testing at a small scale was reviewed.

The potential difficulties of reproducing natural conditions for maintaining mussels on a laboratory scale were recognized fully. However, to proceed effectively with the development of fouling-control treatment, it was essential that it be based upon the characteristics and protective measures of the individual mussel. These could be observed much more accurately in small-scale tests, if natural conditions could be simulated sufficiently well.

Uncertainty may arise in making observations in full-size circulating-water tunnels of power stations because small mussels may enter through the meshes of the screen, so that the time during which a given group of mussels has been subjected to treatment is uncertain. With intermittent treatment, mussels may move considerable distances along the interior walls of the tunnel during the intervals between inspections. Therefore, when the number of mussels in a particular zone changes, generally it is not known whether some have been killed, whether mussels have merely changed location, or whether some have been replaced by new mussels which have recently arrived. In small-scale tests, on the other hand, a fixed number of mussels can be kept isolated in separate receptacles and the period of treatment given each mussel may be determined definitely.

With small-scale tests, radical changes in control methods may be tried, because there is no need to proceed cautiously, as might be expedient in commercial stations. Hence, at least approximate results should be expected more quickly.

It had been concluded from inspection of plants in actual operation that the most resistant fouling organisms in circulating-water systems along the East Coast were the common mussel[2] and the barnacle.[2] Also, these appeared to be important elsewhere. At stations where these organisms had been brought under control by chlorination, other forms of fouling became insignificant. Barnacles commonly do not grow to great thickness and hence, are not a direct source of difficulty in large tunnels. Therefore, study was concentrated on the common mussel.

Since no other quick approach to the general problem was immediately available, small-scale tests were attempted. The first step was to develop suitable procedure and then to determine its feasibility. When this had been demonstrated, tests of killing treatments were started. The project was continued except for minor interruptions for some 2 years, 24 hr per day. Several tests ordinarily were in progress simultaneously. Thus at different times, hundreds of mussels have been observed, not as masses of fouling, but as individuals, twice a day, often many more times, until dead.

## Initial Tests on Feasibility of Small-Scale Tests

Maintenance of the mussels under reasonably normal conditions proved more successful in the small-scale tests than anticipated.[3] Undoubtedly, further observations will dictate modification of details, but results have seemed reasonably consistent. In general, the mussels under test behaved similar to those in the tunnels. With minor exceptions, the specimens remained in groups and clusters as normally. The results in one test tray are shown by photographs.[4] Fig. 1 shows the initial arrangement of the clusters maintained $2^1/_2$ weeks after starting. Clusters had been formed and secure attachment made within one day of starting. Fig. 2 shows the conditions 6 weeks after placing the first specimens in the tray. No deaths had occurred. The final locations of the clusters are practically identical with the original, although the individual specimens had moved within the clus-

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[2] Identified technically as *Mytilus edulis* and *Balanus*, respectively.

[3] Detail procedure described in Appendix.

[4] Photographs were taken after removing water from the trays.

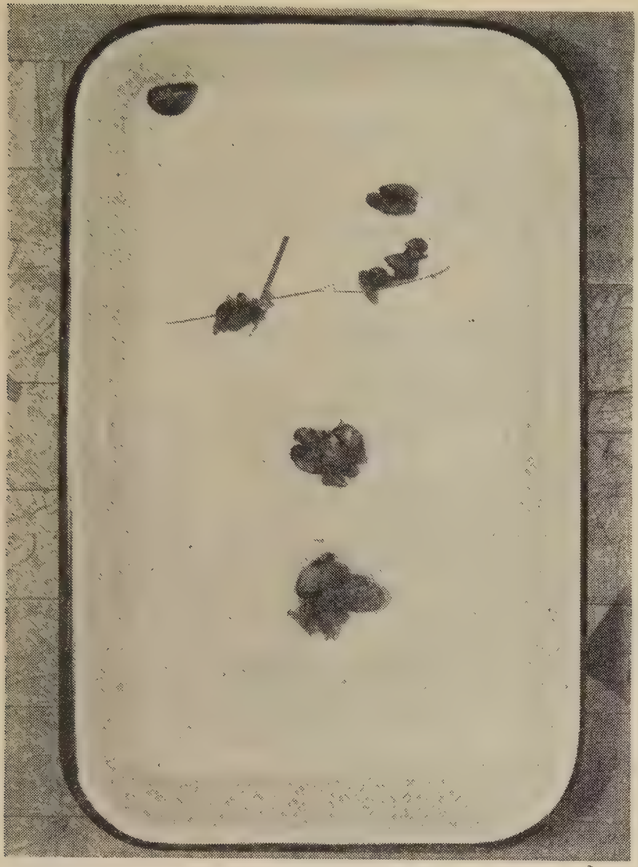

Fig. 1 Live Mussels in Test Tray After $2^1/_2$ Weeks

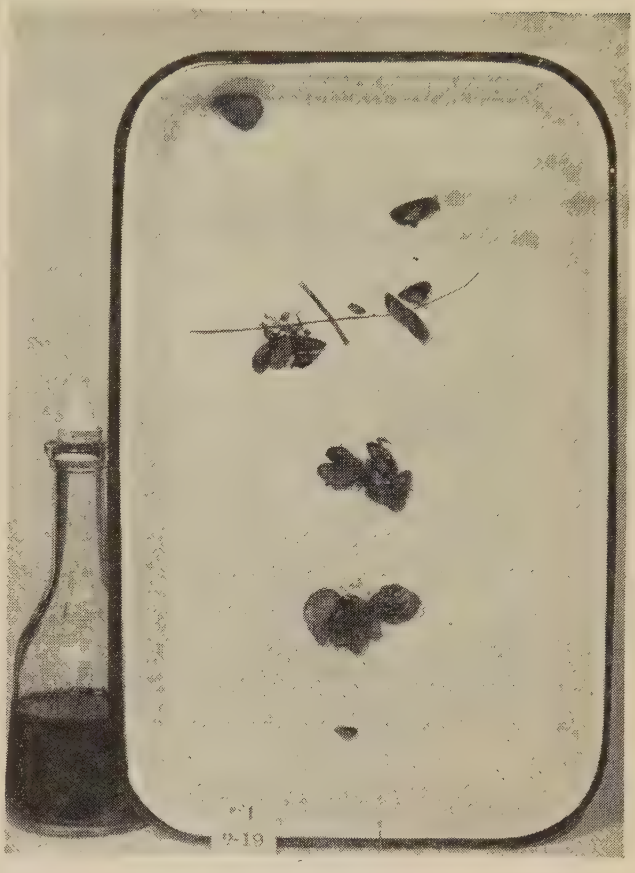

Fig. 2 Live Mussels in Test Tray After 6 Weeks

ters and even transferred from one to another. Two specimens wandered away and started to climb the side wall, but did not continue to the water line as customarily occurs when the condition of the water is unsatisfactory to the mussels. Attachment of the mussels was still firm after 6 weeks.

To illustrate the strength of attachment of the mussels, the entire tray was lifted by grasping the central cluster of mussels by the fingers. The weight lifted was $2^1/_4$ lb which was considered satisfactory for mussels of this size when maintained by batch replacement of the sea water. The specimens maintained mantles[5] well extended throughout the test period and customarily "pumped"[6] for continuous periods of several hours, although continuous flow of sea water in the tray had been used only for a few hours initially. Afterward the sea water in the tray was replaced only twice each 24 hr. The mussels remained alive for many days after the test was discontinued and no further replacement of water made. In another test the water had been taken from the ocean up to 4 days before use and, in general, was replaced only at average intervals of 1.3 days. With this adverse treatment only 2 mussels of the original 46 had died at the end of 12 weeks.

These preliminary tests were made at water temperatures of approximately 50 to 60 F. While this temperature range was favorable to longevity, subsequent tests at summer temperatures gave similar results. Although the preliminary trials showed that batch changes of sea water twice a day were adequate for the usual tests with 1-gal trays, containing approximately 50 mussels ranging in length from $^1/_8$ to $1^1/_4$ in., flowing sea water was used as preferable for tests at the higher temperatures. It was concluded, therefore, that with simple precautions the common mussel could be maintained indoors in sea water satisfactorily to permit direct comparison of different control treatments.

## Control Tests

Assurance of reasonably comparable results was obtained during the tests of killing treatments by maintaining simultaneously a segregated portion of the mussels of each batch in natural sea water, but otherwise under conditions as nearly similar to those of the test as feasible. Use of such control specimens is a customary procedure in zoological tests.

In the majority of tests no deaths whatever occurred among the untreated specimens. No more than one died from any group of 20 to 50 specimens used for individual tests. The few deaths among control specimens occurred within 1 or 2 days after removal from their natural habitat. No control specimen was lost at any later stage. Hence, the few random deaths of control specimens were not associated with the test manipulation but, rather, were considered the result of earlier natural conditions. The total number lost by deaths under control conditions were so few as to be negligible in comparison with the number killed by the treatment and thus have no significant effect on the conclusions.

## Preliminary Tests of Mussel-Control Treatments

In preliminary tests early in 1947, it was observed that it took more than 6 weeks to kill shelled mussels by continuous chlorination when the sea-water temperature was 50 F, in comparison with about 1 week at 71 F, as reported by Dobson.[7] This markedly longer killing time at the lower temperature drew attention abruptly to the great significance of moderate temperature changes in the atmospheric range. As early as June, 1947, a preliminary test indicated that at about 83 F, although complete killing occurred sooner with chlorination than without chlorination, the difference was scarcely noticeable. In another early test at the same period, it was found that at about 93 F, killing was only a matter of a day or two without any chlorine whatever. This led to further investigation of temperature effect.

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[5] Mantles are fringed membranes between shells through which sea water is received.

[6] The mussel pumps sea water through his system to obtain food and oxygen.

[7] "The Control of Fouling Organisms in Fresh- and Salt-Water Circuits," by J. G. Dobson, Trans. ASME, vol. 68, 1946, pp. 247–265.

### Important Effect of Temperature of Water During Chlorination

Quantitative results on the effect of temperature of the sea water during chlorination are summarized in Table 1 and presented graphically in Fig. 3, showing the observed effect of various water temperatures on the rate at which shelled mussels are killed by continuous chlorination. The result of a test reported by Dobson[7] at the single temperature of 71 F, approximately, for partial killing is shown for comparison and correlates satisfactorily. It will be noted that the time required for complete killing at 85 F is only 3 days, whereas at 55 F, the required time is something over 33 days, more than 11 times as great. This brings sharply to attention the very long time required to kill mussels of the Northeast Coast at natural sea-water temperature in winter and early spring.

All results obtained confirm the indication of the preliminary tests that the temperature of the sea water during chlorination is the most important factor controlling the time required to kill normal shelled mussels. The deviation of results of individual tests from the curves suggests that other variable factors may be present, but subsequent tests to date indicate that they have far less effect than temperature of the water during the killing treatment.

Fig. 4 shows the data of Fig. 3 on "semilogarithmic" plotting paper. A straight-line "curve" appears to represent the data reasonably well. This is convenient because, when making tests under other conditions, a few reliable test points near the ends of

TABLE 1 EFFECT OF MODERATE TEMPERATURE CHANGE ON TIME FOR COMPLETE KILLING OF SHELLED MUSSELS BY CONTINUOUS CHLORINATION

| Test no. | Temperature of sea water during test, deg F | Time to kill entire group of mussels, hr[a] | Number of specimens | Date of starting test | Notes |
|---|---|---|---|---|---|
| 1 | 54.8 | 776 | 30 | Nov. 28, 1948 | (*a*) |
| 2 | 74.8 | 240 | 32 | June 12, 1948 | (*a*) |
| 3 | 88 | 42 | 25[b] | June 18, 1947 | (*a*) |
| 4 | 89 | 57 | 38 | Jan. 25, 1948 | (*b*) |
| 5 | 91.5 | 32 | 24 | Feb. 7, 1948 | (*b*) |
| 6 | 105 | $19^1/_2$ | 46 | Mar. 20, 1948 | (*b*) |

[a] Temperature was maintained continuously for time indicated as measured after temperature of water in test tray exceeded 70 F.

[b] Approximate.

General Data: All mussels and sea water for the tests were collected at Lynn Harbor, Mass. Range of temperature: 31 F to 70 F. Typical length of mussels: $^1/_8$ to $1^1/_4$ in.

Notes:
(*a*) Sea water in test tray replaced twice daily in batch for this test.
(*b*) Continuous flow of sea water for this test.

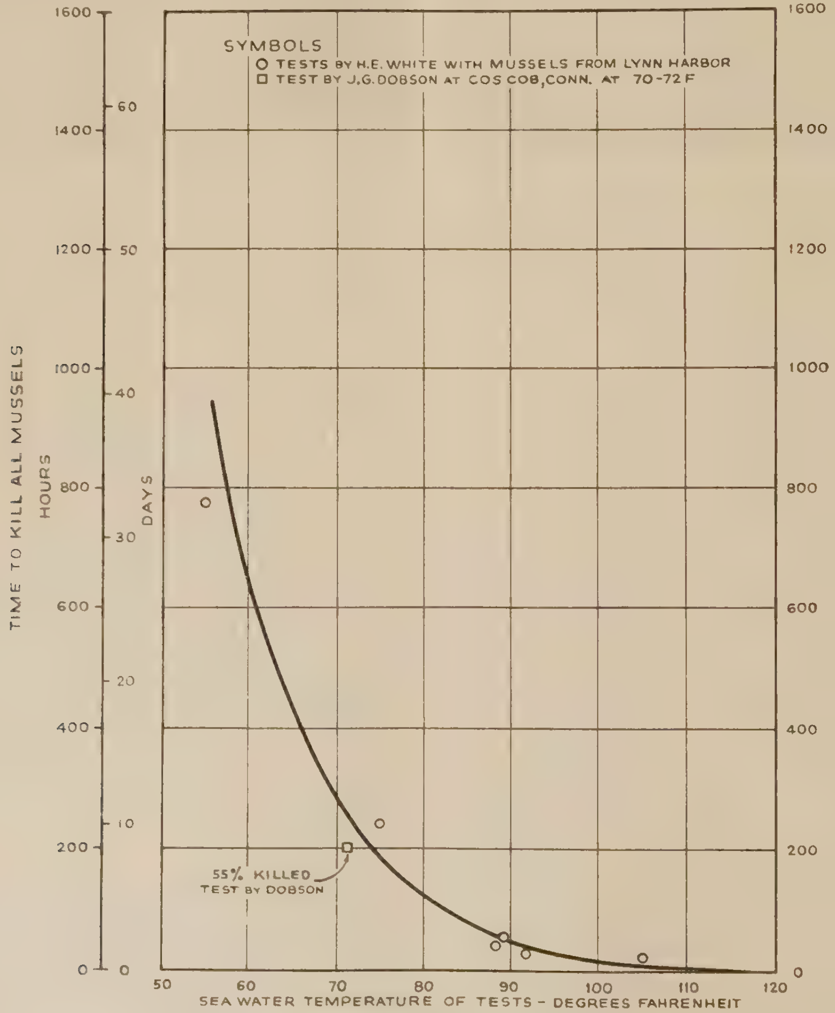

Fig. 3 Effect of Moderate Temperature Change on Time for Killing Shelled Mussels by Continuous Chlorination

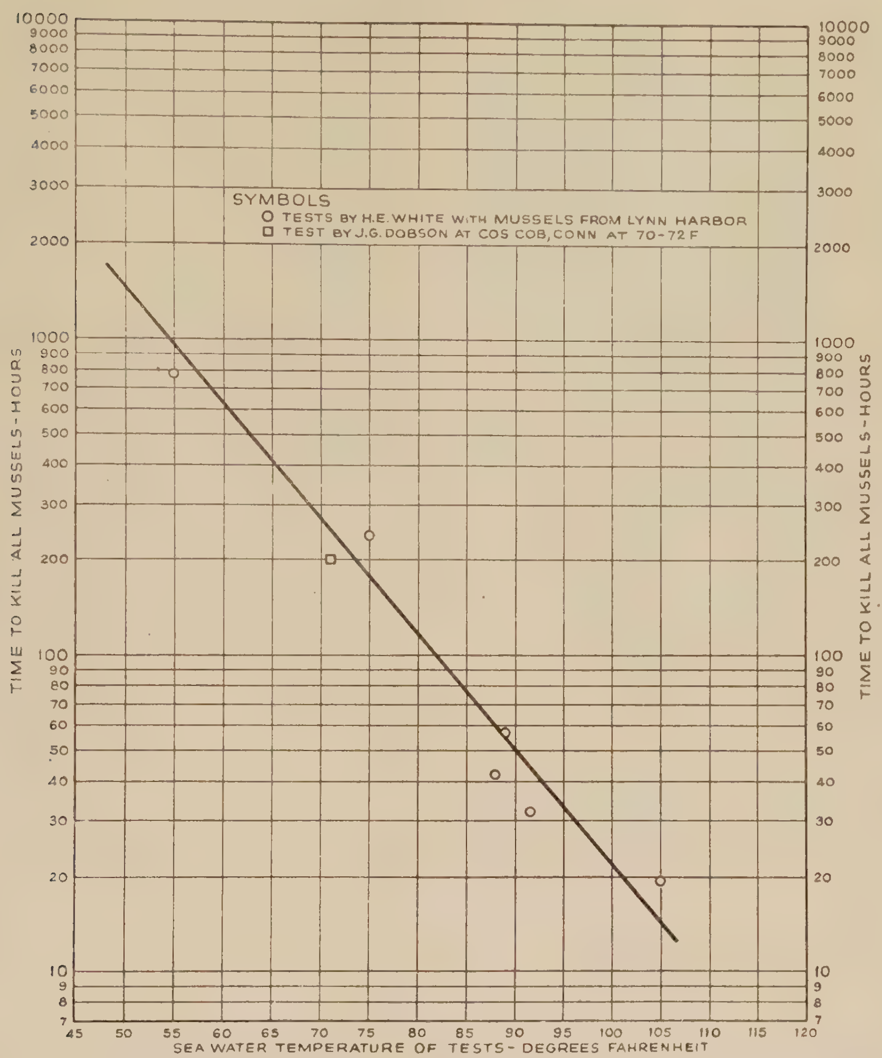

Fig. 4 Effect of Moderate Temperature Change on Time for Killing Shelled Mussels by Continuous Chlorination
(Semilogarithmic co-ordinates.)

such a curve will establish a satisfactory basis for chlorination control.

During the tests with flowing sea water at the higher temperatures residual chlorine concentrations were maintained at 3 to 0.3 ppm. Hence at temperatures above 88 F the results closely approximate those to be expected in commercial operation. In the tests at lower temperatures the sea water was changed by complete replacement twice a day. The initial concentration of residual chlorine in these was high, but the chlorine was consumed progressively until restored with the next change of water. The average concentration was of the order of 10 to 15 ppm, and more at times. For these tests the resultant killing time probably is too low for the usual commercial concentrations, possibly by 20 per cent.[8]

## Results of Killing Tests by Moderate Heating Only—Without Chlorination

Preliminary tests had indicated that at temperatures approaching 90 F and higher there was very little difference in time required to kill shelled mussels, whether chlorine was used or not. To study this further a series of tests was conducted without any chlorine whatever. The tests with temperatures of 90 F and above were made with continuous change of sea water and water-bath equipment.[9]

Obviously, in the absence of chlorine, or other chemical treatment, no killing could be expected at temperatures of 70 F or less, as these temperatures would approach those of natural sea water. However, under the conditions of test, shelled mussels from Lynn Harbor were killed without any chlorine whatever, at a temperature as low as 75 F, by maintaining that temperature continuously for a sufficient length of time. This proved to be more than 12 weeks (test No. 7). Also, observed results confirmed the preliminary conclusions that, at elevated sea-water temperature, chlorination does not reduce the time to kill.

The quantitative results of this series of killing tests without any chlorine or other chemical treatment are summarized in Table 2, presented graphically by the chart, Fig. 5, and plotted on semilogarithmic co-ordinate paper in Fig. 6. In this case a single straight line cannot be applied to the semilogarithmic relation of the data. An abrupt increase in time to kill East Coast mussels is apparent at temperatures slightly less than 85 F.

It will be noted further that above 85 F the time required to kill by continuous heat is approximately the same as when chlorine is used at these temperatures.

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[8] Rough estimate based on tests by Dobson at various concentrations at constant temperature.

[9] See Appendix for test equipment.

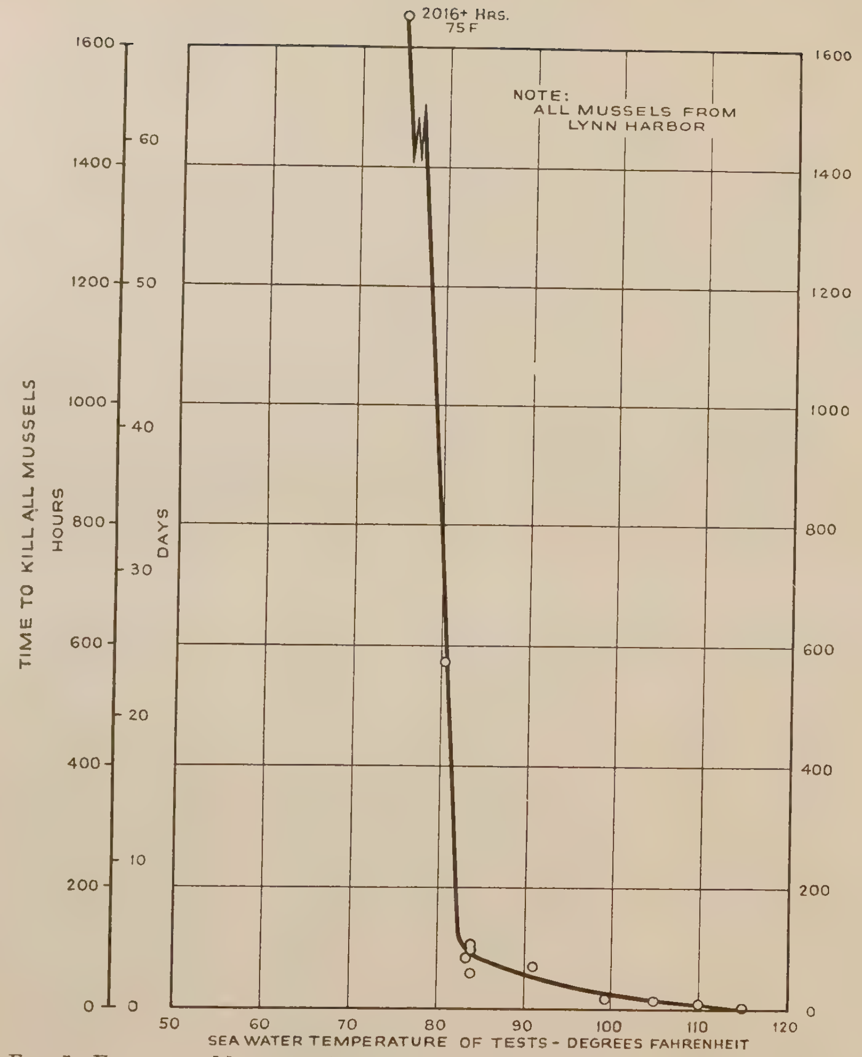

Fig. 5 Effect of Moderate Temperature Change Only on Time for Killing Shelled Mussels—Continuous Treatment

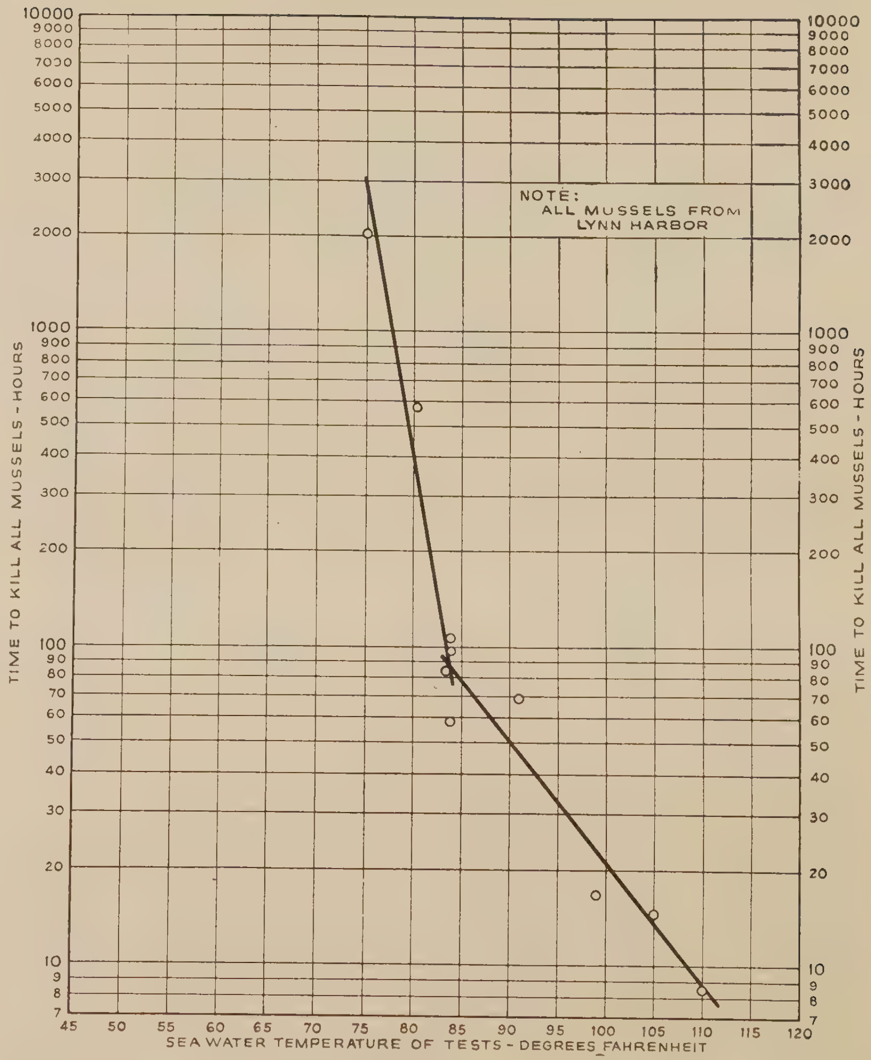

Fig. 6 Effect of Moderate Temperature Change Only on Time for Killing Shelled Mussels—Continuous Treatment

(Semilogarithmic co-ordinates.)

TABLE 2 EFFECT OF MODERATE TEMPERATURE CHANGE ONLY, ON TIME FOR COMPLETE KILLING OF SHELLED MUSSELS, NO CHEMICAL TREATMENT USED

| Test no. | Temperature of sea water during test, deg F | Time to kill entire group of mussels, hr[a] | Number of specimens | Date of starting test | Notes |
|---|---|---|---|---|---|
| 7 | 75 | 2016+[b] | 14 | June 12, 1948 | (*a*) |
| 8 | 80.4 | 572 | 51 | June 9, 1948 | (*a*) |
| 9 | 83.4 | 110 | 53 | July 17, 1948 | (*a*) |
| 10 | 83.9 | 97 | 38 | Sept. 6, 1948 | (*a*) |
| 11 | 83.9 | 58 | 32 | Nov. 6, 1948 | (*a*) |
| 12 | 83.4 | 84 | 25[c] | Nov. 11, 1948 | (*a*) |
| 13 | 91 | $69^{3}/_{4}$ | 13 | Feb. 20, 1948 | (*b*) |
| 14 | 99 | $16^{3}/_{4}$ | 24 | Feb. 26, 1948 | (*b*) |
| 15 | 105 | $14^{1}/_{2}$ | 51 | Mar. 6, 1948 | (*b*) |
| 16 | 110 | $8^{1}/_{2}$ | 43 | Mar. 14, 1948 | (*b*) |
| 17 | 115 | $1^{1}/_{4}$ | 19 | Mar. 14, 1948 | (*b*) |

[a] Temperature was maintained continuously for time indicated as measured after temperature of water in test tray exceeded 70 F.

[b] One mussel still alive and recovered subsequently.

[c] Approximate.

General Data: All mussels and sea water for the tests were collected at Lynn Harbor, Mass. Range of temperature: 31 F to 70 F. Typical length of mussels: $^{1}/_{8}$ to $1^{1}/_{4}$ in.

Notes:

(*a*) Sea water in test tray replaced twice daily in batch for this test.
(*b*) Continuous flow of sea water for this test.

### Comparison of Chlorination, Thermal Treatment, and Combinations

Fig. 7 shows direct comparison of killing time, for continuous treatments with and without chlorine, for various water temperatures. Fig. 8 shows the same comparison with semilogarithmic co-ordinates.

From these charts it is obvious that at a temperature of 80 F or less the time required to kill was reduced greatly by chlorination as compared with no chlorination. At 70 F or lower, temperature alone will not give complete killing in any practical operating period, and use of chlorination or other treatment is required.

Conditions at an existing station may determine the most appropriate treatment or may preclude control of fouling by moderate heating alone. In the latter case chemical treatment may be desired. In the case of new construction, a choice may be available in the design stage. Where provisions in construction permit, moderate increase in temperature alone will give positive and complete killing in a predetermined period of 1 to 3 days with no chlorine or other chemical treatment.

If adequate temperature can be maintained at little cost as, for example, during light load periods at a power station, chemical treatment may offer little or no advantage for killing shelled mussels.

### Technical Conclusions

The most troublesome form of marine fouling observed in stationary conduits was the common mussel.

For complete disposal of marine fouling, it is necessary under usual conditions of commercial operation to kill mussels after their shells are fully developed.

Under all conditions tested, a large proportion of the mussels

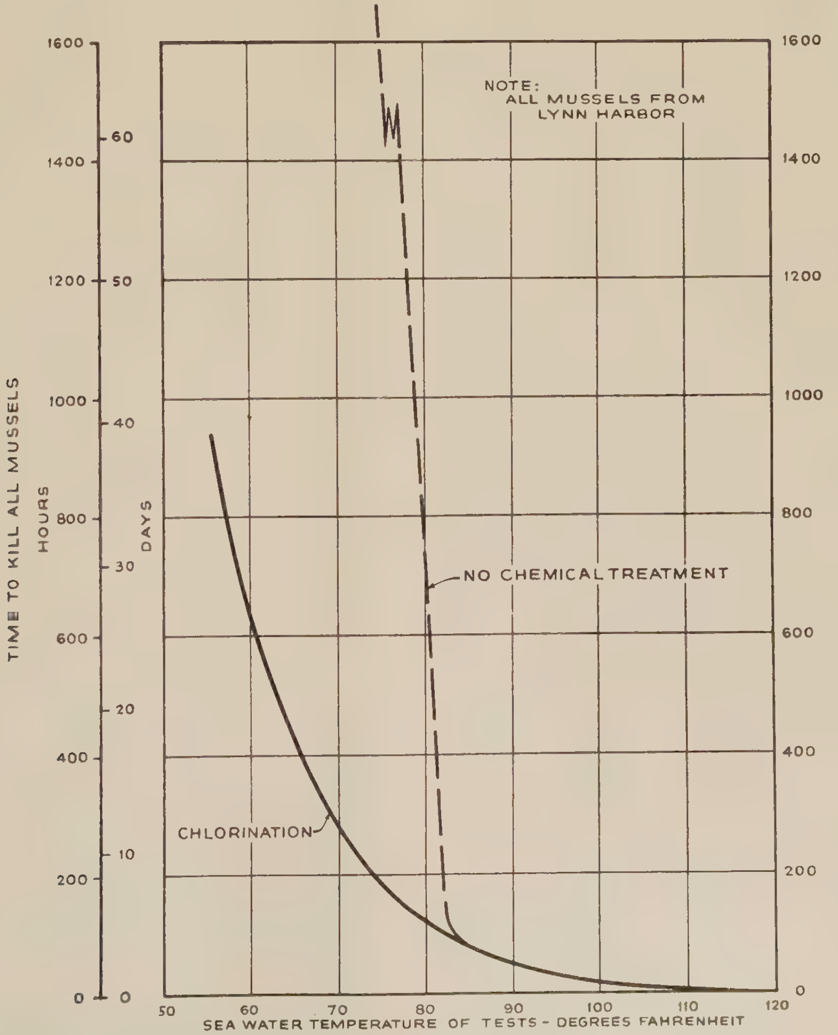

Fig. 7 Comparative Time for Killing Shelled Mussels—Continuous Treatment

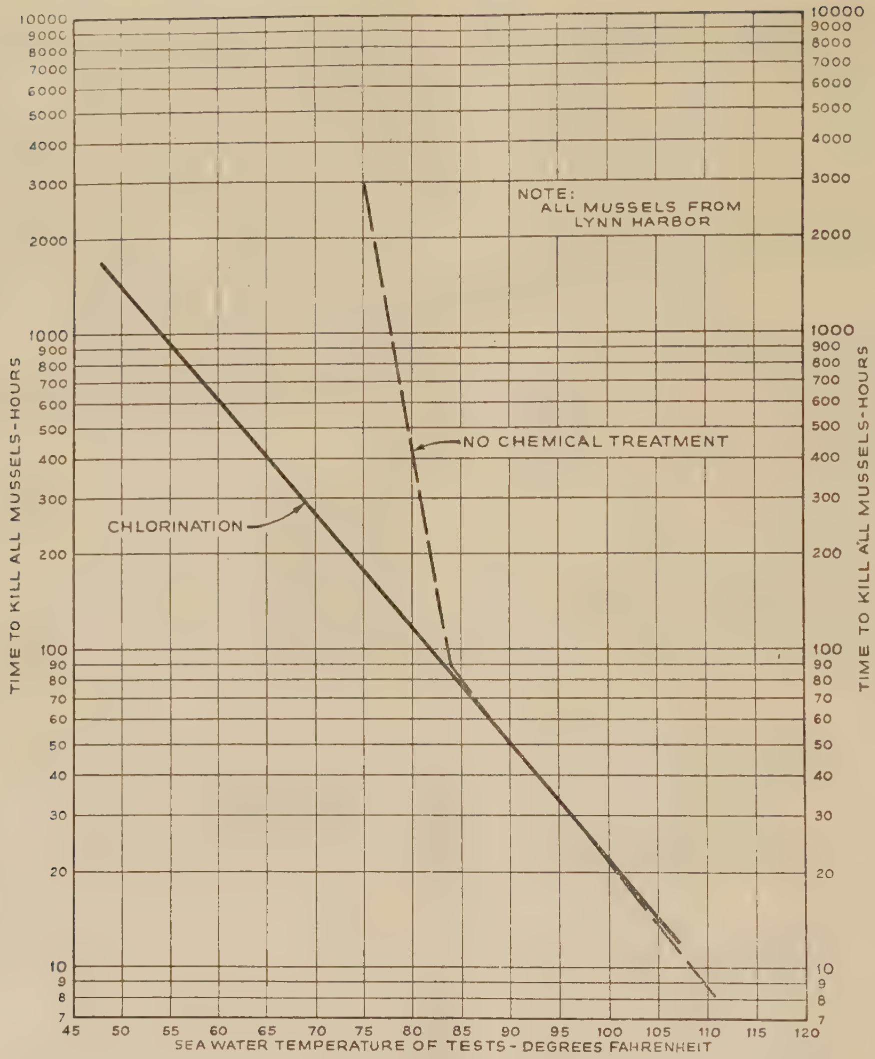

Fig. 8 Comparative Time for Killing Shelled Mussels—Continuous Treatment
(Semilogarithmic co-ordinates.)

are killed within a fraction of the time required for killing all. This is significant because, in a power-station circulating-water tunnel, it is desirable, if mussels have accumulated, to remove them gradually so as to prevent clogging by sudden release and accumulation of uncontrolled masses of debris.

The chlorine consumption required to kill shelled mussels can be reduced greatly by increasing the temperature of the water moderately during chlorination.

The time required to kill shelled mussels by chlorination depends primarily upon the temperature of the water in which they are submerged at the time of chlorination. This is a much more significant factor than the variations of the concentration of the residual chlorine within the usual commercial range.

The most significant reduction in chlorine consumption by increasing the temperature of the sea water is obtained at the lower temperatures and for moderate temperature increases.

Complete killing of shelled mussels may be accomplished by the application of moderate increase in temperature alone, with no chlorine or other chemical agent, if applied continuously for sufficient periods.

There are logarithmic relationships between the time required for complete killing and temperature of sea water during killing treatments.

The following conclusions on killing of shelled mussels from Lynn Harbor apply specifically at that location only. They are significant, however, because, generally, similar results may be expected elsewhere, although at different temperature levels:

By increasing temperature of the sea water from 60 F to 70 F, the time required and the chlorine consumption for killing shelled mussels by continuous chlorination are reduced approximately 50 per cent.

With sea-water temperatures raised to 80 F or less, heat alone is quite inefficient for killing shelled mussels, and the use of chlorination or other treatment is indicated.

With sea-water temperatures increased to 85 F, continuous chlorination does not reduce the time for killing below that for continuous temperature without chemical treatment.

When the sea-water temperature is approximately 50 F, the time required for complete killing of shelled mussels by continuous chlorination is about 2 months.

The time required for complete killing of shelled mussels by temperature alone at 90 F was 80 per cent less than with chlorination at 70 F.

## Conclusions on Technique of Small-Scale Test Procedure

It was demonstrated that with natural sea water at natural temperatures, shelled mussels could be maintained in sea water in small receptacles indoors for many weeks in satisfactory condition for comparative tests of killing treatments if reasonable care was exercised in maintaining the natural condition of the sea water by replacing it periodically.

Many useful observations can be made by small-scale tests if the results are considered on a comparative basis, and if a few simple precautions are observed under the guidance of a qualified consultant. This is particularly convenient when it is considered impractical to try changes in the existing method for control of fouling in a commercial power station under heavy demands for power.

Because of the very large variation in the time periods required to kill individual specimen mussels of a given lot under the same treatment, it is important to use a reasonably large number of specimens for a given test in order to determine even approximately the time required to kill all the mussels under a given set of conditions. In general, a minimum of 50 specimens is suggested.

In many tests it was observed that mussels showing the greatest resistance were those of small size, $^1/_2$ in. long and less; hence these sizes should be included in each batch tested to assure determination of maximum killing time.

It appears desirable to establish a suitable criterion with respect to the varying physical condition of a mussel, or more specifically the resistance to killing. The time required to kill a representative group of 50 specimens by a standard procedure which would approximate a commercial control treatment has been used by the author.

### APPLICATION

The small-scale tests have shown that mussels can be exterminated totally on various predetermined schedules of treatment.

The results of the tests are considered adequate for application to routine control of marine fouling of the Northeast Coast if used with liberal factors of safety. Such factors are required in any case because of the considerable variations in the condition of the natural water from time to time and the variations in the condition of the mussels at a given site. If, however, mats of mussels have been allowed to form in the tunnel, or other kinds of fouling must be removed first, it is expected that the time required for killing by continuous chlorination would be increased.

The results of a selected treatment may vary greatly with only moderate changes in conditions. Also, different degrees of control may be desired for different plants because of economic, constructional, or operating conditions. In order to set up a suitable schedule of control treatment at a given plant, therefore, specific quantitative information is desirable. Hence, local tests at the site for each season are recommended.

If for any reason initial treatment in the plant should prove inadequate, it would be necessary only to increase the duration of the treatment or possibly to increase the water temperature gradually, within the limitation of permissible differential temperature stress where massive concrete structures are involved.

The particular type of control for marine fouling to be selected as most appropriate for a given plant would depend on local conditions, including geographical location, fresh-water dilution, if present, industrial pollution, length of tunnel, access, operating conditions, station load conditions, station design, and the like. This subject, however, is beyond the scope of the present paper.

General results have broad application. Although tests were carried out primarily in connection with the protection of circulating-water systems of power stations, corresponding problems of marine fouling may occur at any coastal plant where natural sea water is used, for example, in salt-water service pipe lines of industrial plants and salt-water fire lines. Salt-water piping systems aboard ships are not immune.

### ACKNOWLEDGMENTS

This project has now extended over several years. Throughout we have had the most generous co-operation of a large number of people whose help is gratefully acknowledged. The advice of the following consulting marine biologists was particularly valuable: Dr. William F. Clapp, William F. Clapp Laboratories, Inc.; Dr. Denis L. Fox, Scripps Institution of Oceanography; Dr. Louis W. Hutchins, Woods Hole Oceanographic Institution.

Many power-station operating organizations on both the East and West Coasts have afforded us the advantage of inspection of circulating-water systems when feasible, and full discussion of operating techniques and results. We are particularly grateful to the executives and engineers of the Southern California Edison Company, Long Island Lighting Company, and Lynn Gas and Electric Company. Even from West Africa we received a most painstaking report on practical operating experience with a long submerged tunnel resting on the ocean floor.

The author wishes to express his personal appreciation of the continued interest and help of Mr. William F. Ryan, engineering manager, and Mr. E. B. Powell, consulting engineer, of Stone & Webster Engineering Corporation.

## Appendix

### TEST PROCEDURE

The general procedure developed in carrying out this series of tests was as follows:

Mussels, as collected from their ocean-shore surroundings, were first retained in trays of natural sea water at moderate room temperature until they functioned in an approximately normal manner before tests were started. The time required to kill the specimens by various treatments was then observed. During the winter, when specimens were taken from their natural habitat at temperatures between 31 F and 45 F, a period of gradual temperature rise of the sea water in the test vessel was allowed before starting the killing test.

For the tests at temperatures of 89 F and above, continuously flowing sea water was used. For other tests it was an essential detail of the technique to renew the sea water in the test receptacles twice daily by emptying and replacing completely so that the water in every part of the test receptacle would be changed.

Mussels for all tests reported were collected at the northeast end of Lynn Harbor on a rocky beach where rubble had been dumped. The harbor extends into an industrial area and has a typical range of tidal elevation of about 10 ft. Size of specimens varied from $^1/_{16}$ in. to $1^1/_2$ in.

Sea water used throughout the tests was taken from the same location in the harbor except on a few occasions when there appeared to be some local contamination. At these times other zones in the same harbor were used.

Sea water used for the control tests was collected from the same source and at the same time as that for the main tests.

Temperature of the sea water in the test receptacles was observed by glass-stem chemical thermometers.

Zonite was used as a convenient source of chlorine.

### TEST EQUIPMENT USED

In the tests with water temperatures above 88 F, enameled trays of approximately 1 gal capacity were used with continuously flowing sea water. The arrangement of the equipment used for each test, however, was no more complex than that shown by preceding tests to be necessary. More refinement was required as the water temperature was increased. At approximately 30 deg F above room temperature it was necessary to minimize variations in water temperature during the test, and also to prevent

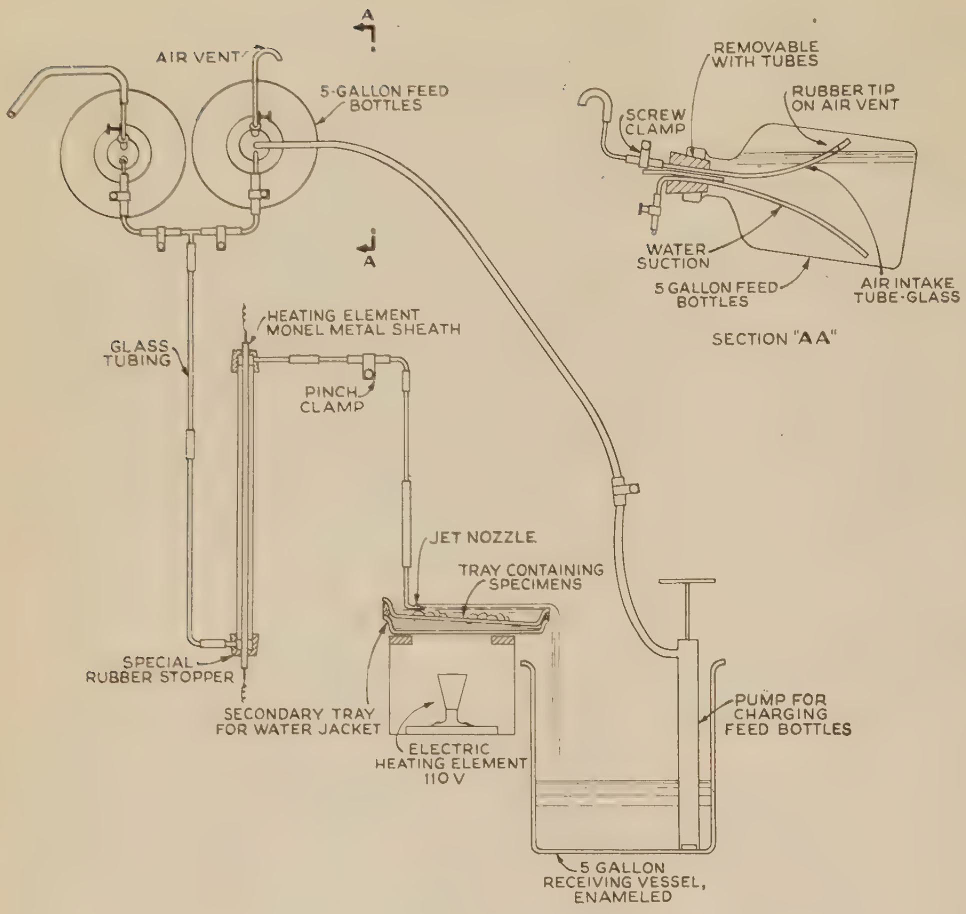

Fig. 9 Diagram of Test Equipment

nonuniform distribution of temperature across the tray. The equipment adopted is shown in Fig. 9. Uniformity of temperature in the test tray containing the mussels was promoted by the use of a second tray of heated water directly below, acting as a water bath. The temperature of the water bath was controlled by adjusting the elevation of the radiant electric heating elements below the tray. Continuous replacement of the sea water was provided by a small jet supplied from overhead. It was found that the jet of incoming water was sufficient to maintain continual mixing of the water within the tray and thus assure uniform distribution of temperature throughout the test tray. The temperature of the sea water from the jet was raised to approximately that of the water in the test tray by first passing it through a tubular-type electric water heater of special design. The use of a small jet minimized the required capacity of the heater.

Even with a jet approximately 0.02 in. diam, mixing was entirely effective when the static head was only 2 ft, and, with a jet of this small size, it was possible to maintain the siphoning of sea water from the 5-gal bottles overhead for a period of several hours without refilling. No plugging of the small orifice occurred, as the large bottles permitted effective settling of suspended matter in the sea water.

The temperature of the water in the test tray has been shown to be a critical factor, and should be maintained nearly constant for a given test. Since manual adjustments required almost continual corrections at the higher temperatures, an automatic temperature control is recommended to reduce the attendance and to improve precision.

## Progressive Killing

In the earliest tests, it was apparent that the time required to kill shelled mussels by a given procedure varied over a wide range for the individual specimens of a single group in the same test tray and subjected to the same conditions. This is illustrated by the chart in Fig. 10 which shows the rate at which deaths occurred. All subsequent tests confirmed that individual mussels of a given group under test died in succession, suggesting significant differences between the resistance of individual mussels of a group, all of which had lived under the same natural conditions. It was shown, however, that if a considerable number of specimens were used for each test, the time required to kill the entire group gave reasonable correlation of results of various tests. This led to the conclusion that the work should proceed on a statistical basis. Because of the more consistent correlation of the "time to kill all mussels" of the various test groups, this measurement afforded a more satisfactory means of showing the fundamentals involved; therefore the time to kill, as reported in Tables 1 and 2, is that required to kill all mussels of the particular group under test by continuous treatment until dead.

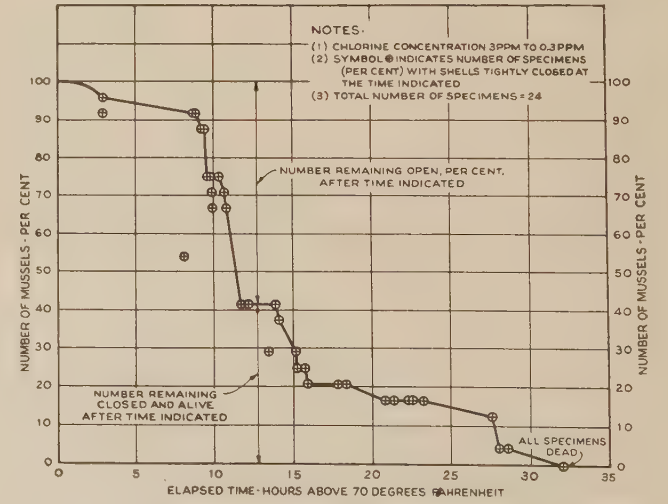

Fig. 10 Rate of Killing Shelled Mussels at Given Temperature Level

# Thermal Control of Marine Fouling at Redondo Steam Station of the Southern California Edison Company

By W. L. CHADWICK,[1] F. S. CLARK,[2] and D. L. FOX[3]

**The idea of controlling marine fouling by elevating the temperature of the sea water is not new, but it is felt that the application of this means of control in the cooling-water tunnels at the recently constructed Redondo Steam Station of the Southern California Edison Company at Redondo Beach, Calif., contains some features of interest. It is the object of this paper to describe the system employed and to present the results obtained during the first year of operation.**

## Design Considerations

PRIOR to designing the Redondo Station, it had been observed at the company's Long Beach Station that, whereas heavy fouling growths occurred in the intake tunnels, no serious fouling growths occurred in the discharge tunnels, even though these had never been cleaned in the history of the plant. The only difference in the tunnels to which this freedom from growth could be attributed was the higher temperature of the water in the discharge lines. In designing the Redondo Station, it was decided to utilize this condition to the maximum extent practicable, and also to provide facilities for chlorinating the water in the lines should treatment by higher temperatures not be fully successful.

The Redondo Station is situated on a section of sea coast that is exposed to winter storms and resultant heavy wave action. Hence it was highly desirable to have no structure offshore which would rise above the water and be subjected to pounding by large waves. Also, the beach at the plant site is one of the most popular in Southern California, and consequently no structures could be used that would interfere with the recreational use of the beach by the public.

These considerations precluded the use of a trestle or other structure to support chlorinator lines and a tower at the seaward end to house the chlorine apparatus, but led to the suggestion that two separate submerged lines be constructed out into the sea each of which could be used alternately as an intake or discharge, controlled by flow-reversing gates located on the shore end of the lines.

## Thermal Sensitivity of Marine Fouling Animals

Biochemical control measures are commonly employed in combating marine fouling. These may involve the application of toxic paint surfaces to immersed structures such as ships' hulls, or the introduction of chlorine, organic chlorides, or other poisonous solutes into the moving streams of an enclosed system.

However, in an electric power-generating steam plant, utilizing flowing ocean water for cooling its condensers, a rather unique opportunity is offered for an introduction of a biophysical control feature, namely, heat. Two large tunnels at the Redondo plant of the Southern California Edison Company, each 10 ft ID, and extending for nearly 1900 ft into the open sea, are employed as intake and discharge channels, being alternated in these two functions at intervals of 2 to 4 weeks, depending upon the fouling season. Thus the periodic discharge of sea water through each tunnel at elevated temperatures has prevented the growth of fouling animals which have been observed in systems not accorded this treatment.

Experiments at the Scripps Institution of Oceanography reveal the fact that numerous sedentary marine invertebrate animals possess relatively sharp temperature-tolerance thresholds. Sedentary marine algae have not been investigated here, since they fail to colonize dark environments, and hence do not constitute a part of the fouling communities therein. Mussels, barnacles, sponges, tunicates, bryozoa, tube-worms, and anemones constitute the chief sources of trouble. In the Redondo and San Diego areas, the common mussel, *Mytilus edulis*, is the most prevalent member of fouling communities in sea-water tunnels. Barnacles, sponges, and tunicates are secondary foulers, while the large California mussel, *Mytilus californianus*, is an occasional invader at localities employing water from the open sea as distinguished from bays and estuaries which support only the other species, *Mytilus edulis*.

It has been found that the bay mussel, *Mytilus edulis*, is more resistant to exposures in warmed sea water than are *Mytilus californianus*, the barnacles *Balanus tintinnabulum*, *Balanus glandula*, the anemone *Cribrina xanthogrammica*, and other forms. *Mytilus edulis* is exceeded in this respect only by the small ribbed mussel, *Septifer bifurcatus*, but the latter species is so small and relatively sparse in numbers it does not constitute a serious threat.

In order to define working conditions which should hold promise for the practical thermal control of fouling, we therefore selected *Mytilus edulis* as representative of the most populous and relatively resistant fouling organisms common to these waters. Groups of young individuals (about 5–10 mm long, some 3–4 weeks old) were separated carefully and immersed in sea water at closely controlled temperatures for designated lengths of time. At the end of each experimental period, the animals were returned to running sea water and observed for possible survival. Survivors soon part their shells moderately, filter currents of sea water through their siphons, and attach themselves to solid surfaces by spinning the tough threads of adhesive byssus in the normal manner. Thermal casualties part their shells in a gaping fashion, die, and undergo decomposition of the flesh.

The following data have been collected relative to young specimens of *Mytilus edulis:*

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[2] Consulting Engineer, Stone & Webster Engineering Corporation, Boston, Mass. Fellow ASME.

[3] Professor of Marine Biochemistry, Scripps Institution of Oceanography of the University of California, La Jolla, Calif.

Contributed by the Power Division and presented at the Spring Meeting, New London, Conn., May 2–4, 1949, and at the Semi-Annual Meeting, San Francisco, Calif., June 27–30, 1949, of The American Society of Mechanical Engineers.

Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—S-13.

| Temperature, deg F | Thermal death time, hr |
|---|---|
| 106 | 0.33 (20 min) |
| 100 | 1 |
| 95 | 6–7 |
| 90 | 13 |
| 85 | 41 |
| 82 | 96 |
| 77 | Survive indefinitely |

A graph of the foregoing data yields a smooth exponential curve. It is believed that swimming or freshly settled mussel larvae, being without shells, metabolically active and relatively more sensitive to unfavorable environmental factors, doubtless succumb more readily than do the young individuals which have formed their shells and undergone growth. Thus plant practice, guided by the foregoing data in the Southern California area, provides a generous margin of safety, especially provided that (1) at the height of the marine reproductive season (i.e., from early spring to late fall), water flow is alternated sufficiently frequently (at least every 2 to 4 weeks) to affect the larval or juvenile animals before they have had time to become firmly established, and (2) that temperatures within the upper range are maintained for the periods correspondingly indicated.

Moribund mussels reveal their condition in several observable ways, e.g. (1) by gaping, (2) by failure to close their valves upon mechanical stimulation (tapping the shell), (3) by failure to spin byssus strands for attachment, and (4) by decomposition of their fleshy parts. Even if any or all of the first three diagnostic signs are observable in a treated lot of mussels, it is invariably essential to remove the batch of animals and place them in a container of running sea water at normal temperatures. This was always done in our procedure, by having each lot of ten animals in a large porcelain vessel with perforated bottom (a large Gooch crucible).

At the end of an experimental period, a crucible of experimental animals was removed, drained of water, and the mussels were transferred immediately into a container of fresh cool sea water. This latter container, covered by a screen, was then placed in a running sea-water aquarium, and the experimental animals thereafter were observed during periods of several days. Some heat-narcotized sluggish animals later revive under these conditions, spin byssus, and propel water normally through their valves. On the other hand, some small mussels which fail to reveal their death by parting their valves, actually may be found to have died in this condition, the shell hinge being insufficiently rigid to operate conspicuously.

Observations always were continued on all animals given heat-treatment for a defined interval and then restored to natural conditions, until such time as we were able to determine that all died as a result of the heat, or that one or more survived. Thus sometimes the data are not all available for 3 or 4 days after the initial thermal treatment. Our data are all plotted on the basis of 100 per cent mortality.

With the use of this method of collecting reliable data, for example, we were able to obtain typical information relative to a series of mussels exposed to a temperature of 35 C or 95 F as shown in Table 1.

The time of 7 hr was manifestly the approximate period to be adopted as the lethal period for mussels of the indicated size and locality, exposed to a temperature of 95 F. Had we merely observed the condition of our animals in the experimental heating vessel, we should have been unable to collect reliable time data for lethality. The believed lethal period thus might exceed the actual lethal period by several or manyfold.

Manifestly the size range of experimental animals, the manner of heating and supplying reviving conditions, and clearly defined criteria of irreversible heat narcosis, leading to certain death, should all be standardized by experimenters in the field.

The definite possibility remains that mussels or other fouling species may vary somewhat in their thresholds of thermal tolerance, according to temperatures prevailing in their normal habitats. Marine animals living on the coast of the Pacific Northwest, for example, might be expected to manifest greater sensitivity, i.e., succumbing at less elevated temperatures and/or within shorter time intervals, than members of the same species, but possibly constituting a separate "physiological race," inhabiting Mexican waters. The sensitivity of races found at intermediate latitudes probably would lie between two such extremes. These matters should be borne in mind, and should be tested experimentally when contemplating the use of flowing sea water from any given region.

TABLE 1 THERMAL DEATH TIME OF MYTILUS EDULIS[a]

Date of start. 7-27-48 Time of start. 2.00 P.M. Nominal temperature 35 °C. or 95 °F.

| Sample No. | Total No. per sample | Time heated | | Temp °C. | Active | | | Indeterminate | | | | Gaping | | | | % Dead |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Clock | Exp.hrs. | | 7/28 | 7/29 | 7/30 | 7/28 | 7/29 | 7/30 | 7/31 | 7/28 | 7/29 | 7/30 | 7/31 | 7/31 |
| 1 | 10 | 5:00 | 3.0 | 34.7 | 1 | 10 | 10 | 9 | 0 | 0 | 0 | 0 (some sluggish) | 0 | 0 | 0 | 0 |
| 2 | 10 | 6:00 | 4.0 | 34.7 | 0 | 4 | 7 | 10 | 6 | 1 | | 0 (sl) | 0 | 2 | | 20 |
| 3 | 10 | 7:00 | 5.0 | 34.8 | 0 | 0 | 2 | 10 | 3 | | | 0 (sl) | 7 | 1 | | 80 |
| 4 | 10 | 8:00 | 6.0 | 35.2 | 0 | 0 | 1 | 10 | 1 | | | 0 (9 sluggish) | 9 | | | 90 |
| 5 | 10 | 9:00 | 7.0 | 35.3 | 0 | 0 | 0 | 10 | | | | 0 (all sluggish) | 10 | | | 100 |
| 6 | 10 | 10:00 | 8.0 | 35.3 | 0 | 0 | 0 | 10 | | | | 0 (all sluggish) | 10 | | | 100 |

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[a] From records of D. L. Fox.

## DESCRIPTION OF CIRCULATING-WATER SYSTEM

Reference is made to Fig. 1 which shows the facilities for withdrawing water from the Pacific Ocean for the Redondo Station. Two 10-ft-ID precast concrete pipes are laid in the floor of the beach in trenches, having a minimum earth cover of 4 ft, and extend into the sea for a distance of about 1900 ft. The lines were constructed under water by the use of divers, and facilities for unwatering the lines are not provided. The terminal structures are vertical precast concrete towers 14 ft diam, extending about 10 ft above the sea floor and protected by a rock riprap. The top of these towers is about 20 ft below mean lower low water. They are separated laterally by 200 ft to avoid recirculation of the water.

The choice of pipe internal diameter was selected as 10 ft after considering such factors as cost, flow, and possible decrease in diameter by marine growths, with attendant increase in roughness factor. The present pipes will be adequate to handle all the circulating-water requirements for the plant when the latter is expanded to its present ultimate capacity of 264,000 kw. At this load the circulating-water requirement will be about 180,000 gpm.

The shore end of each concrete pipe is connected to a concrete structure in which there are four vertical steel gates which can be raised or lowered with electric motors. The gates are arranged and operated so that one of the concrete pipes acts as an intake and the other as a discharge conduit. At intervals, the position of the gates is changed so that flow is reversed in each conduit. In this way either conduit may be used alternately as a discharge or intake.

Other equipment in the shore structure includes a discharge chamber for warmed water returning from the main condensers in the power plant, a trash rack for collecting and removing seaweed and other trash, revolving screens for removing fish and other marine growth, a suction chamber for the main circulating-water pumps, and a pump house. Circulating water for the main condensers is conveyed from the pumps through 54-in-ID precast concrete pipes laid underground. The latter are not subjected to the antifouling treatment to be described later because it was possible to provide access to them for periodic cleaning by manual means whenever it becomes necessary to do so. Antifouling measures are applied to the two 10-ft-ID pipes under the ocean principally because of their inaccessibility for the usual methods of cleaning.

There is also provided in the pump house equipment for chlorinating the circulating water. Chlorine can be introduced into the water at two places and for two purposes as follows:

1 At the circulating-water pump intake as a desliming agent for the condensers.

2 At the shore end of the 10-ft-ID discharge pipes as a toxic agent for killing marine organisms in the pipe. So far the latter use of chlorine has not been necessary due to the success of the method to be described.

## FLOW REVERSAL

The reversal of the circulating water is effected by four vertical gates, one located in each intake and two at the outlets of the transfer basin or reversing chamber. The gates normally will operate in pairs, one intake and one discharge opening, the other pair closing. Gates are 7 ft wide and 10 ft high, built of fabricated steel. They are provided with cast manganese-bronze guides with bronze sealing strips and with stainless-steel stems. The four gates normally operate together at uniform speed, 4 min being required for the complete stroke. The gate hoists are operated electrically, and the position of each is remotely indicated on both the circulating-water panel board in the steam station and the chlorination control panel on the second floor of the chlorination building.

During the 4-min period of reversal there will be a certain amount of recirculation of warmed water, from that gate which has been the discharge and which is now closing, to the intake, which has been closed and which is now opening. The flow in that tunnel, which has been the discharge, is gradually reversing, and some warmed circulating water will be drawn back into the intake. The effect of the reversal of the circulating water is shown in Fig. 2 in which the elevation of the free water level in the forebay has been plotted against elapsed time following the start of the gate movement. This curve sheet is based upon a circulating-water flow of 400 cfs and on a tide level of 0.0. It will be noted that the water level in the intake basin starts at approximately 3 ft below grade 0.0 (which is the head loss in the intake tunnel) and reaches a maximum low grade just after the gates have completed reversal. This lag is a result of the time required to decelerate and reverse the flow of water in the intake tunnel. Approximately 14 min are required for the re-establishment of equilibrium at a level of 3 ft below grade 0.0 (corresponding to the head loss in the discharge tunnel), and a peak water level of approximately 8.5 ft above grade 0.0 is reached just after the completion of the gate movement.

The foregoing maximum and minimum levels are based on an ocean grade of 0.0, corresponding to mean lower low water. When a low tide at —2.5 or a high tide at 7.0 ft occurs, these tide levels below and above grade 0.0 must be superimposed on the level variation shown in Fig. 2. Additional hydraulic data are shown in Table 2.

A weir has been provided at grade 16.0 in the top of the east wall of the transfer basin. Should simultaneous occurrence of

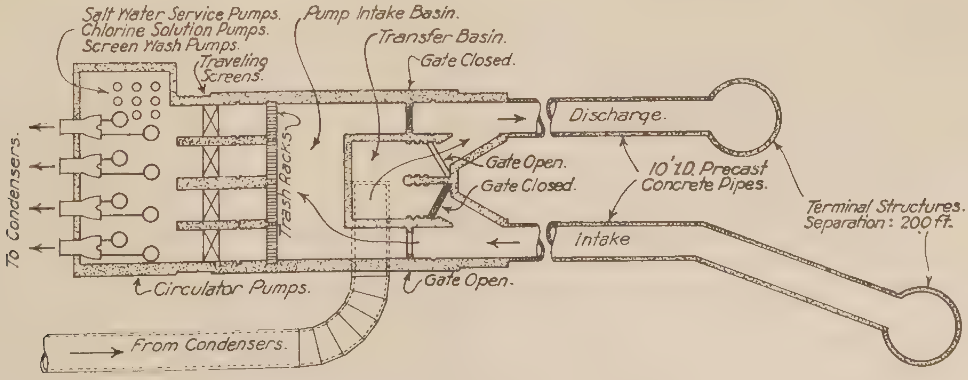

FIG. 1 FACILITIES FOR WITHDRAWING WATER FROM THE SEA FOR THE REDONDO STATION

TABLE 2 ELEVATIONS, HYDRAULIC GRADIENT, AND HEAD LOSSES OF CIRCULATING WATER SYSTEM, REDONDO STEAM STATION

*Elevations:*
(Mean lower low water = 0.0)

| | |
|---|---|
| Top of intake and reversing-chamber structure | 15.0 and 18.5 |
| Bottom of intake and reversing-chamber structure | −19.0 |
| Top of overflow weir reversing chamber | 16.0 |
| Bottom of screen well and pump well | −22.0 |
| Pump-house floor | 5.28 and 15.0 |
| Circulating-pump intake bell | −19.16 |
| Steam station basement floor | 10.0 |
| Center line of condenser intake | 18.5 |
| Top of condenser tail pipe | 25.0 |
| Center line of 10-ft discharge tunnel-condensers to reversing chamber | −2.5 and −2.0 |

*Hydraulic gradient:*
(Based on a flow of 400 cfs with allowance for marine growth on tunnel walls)

| | High water (7.0) | Mean lower low water (0.0) | Low water (−2.5) |
|---|---|---|---|
| Level in intake basin | 3.7 | −3.3 | − 5.8 |
| Minimum level of intake basin, during period of flow reversal | ... | ... | − 9.8 |
| Level in pump well | 2.4 | −4.6 | − 7.1 |
| Minimum level in pump well, during period of flow reversal | ... | ... | −11.1 |
| Level in reversing chamber | 10.3 | 3.3 | 0.8 |
| Maximum level in reversing chamber, during period of flow reversal | 15.8 | ... | ... |

*Head losses:*
(With allowance for marine growth on tunnel walls)

| | Two units, 200 cfs | Four units, 400 cfs |
|---|---|---|
| Alternating intake and discharge tunnel (*L* = 2007 ft) | 0.8 ft | 3.3 ft |
| Screen wells | 0.6 | 1.3 |
| Inlet-pipe line, pumps to condenser | 4.8 | 4.8 |
| Condenser | 16.9 | 16.9 |
| Discharge pipe line, condenser to reversing chamber | 7.9 | 9.8 |
| Alternating intake and discharge tunnel (*L* = 1825 ft) | 0.7 | 2.7 |
| Total | 31.7 | 38.8 |

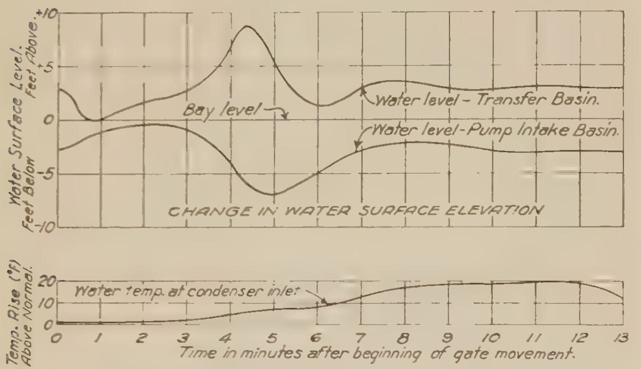

FIG. 2 EFFECT OF REVERSAL OF CIRCULATING WATER

maximum flow, flow reversal, and high tide cause this basin to overflow, the excess water will discharge into the intake basin.

For a short period following tunnel reversal, condensers will receive warmer than normal circulating water owing to the recirculation which occurred when all four gates were open and changing, and to the reversal of the flow in that tunnel which had been the discharge and which became the intake. Fig. 2 indicates that a temperature rise above normal may persist for some 12 min, with a peak rise of 19 deg F prevailing for 3 min. This calculated rise of inlet-water temperature above normal is based upon a heat rejection of 1720 × $10^6$ Btu per hr to the circulating water corresponding to the extreme conditions of four units operating at 66,000 kw. For any lower station load, the magnitude of this temperature rise will be proportionally reduced. It has been found by experience that the reversal cycle does not affect the ability of the main units to carry full load.

### Electric Control of Reversing Gates

Each of the four gates is provided with an electric motor operator and means for automatic and manual position control. Automatic control, under which all four gates operate in synchronism, two opening and two closing, is derived from the chlorination control panel. A manual switch for positioning the four gates synchronously is located on the chlorination panel, while local switches permit the positioning of individual gates. A position indicator for each gate is located on the chlorination control panel and the circulating-water panel in the steam station.

Indicating lights are provided at the chlorine control board and at the motors to show the position of the gates. Red indicates gate fully open. Green indicates gate fully closed. Red and green together indicate gate is either moving or stopped in an intermediate position.

After a gate-positioning operation has been initiated, should an obstruction or a power failure cause any one of the gates to stop before completion of one half of its travel, all gates reverse their travel and are restored to the same position as before operation was initiated. In case the gates have completed more than one half of their travel before one gate stops, all other gates complete the operation. An alarm will sound at the circulating-water gage board if gates go out of synchronism.

### Basis of Present Treatment

The marine fouling organisms which are particularly troublesome at this location are as follows:

1 Bay mussel (*Mytilus edulis*).
2 Large sea mussel (*Mytilus californianus*).
3 Barnacles (*Balanus tintinnabulum* and *Balanus glandula*).
4 Hydroids.

Laboratory investigations at the Scripps Institution of Oceanography, University of California, indicated that, of those organisms listed, *Mytilus edulis* is the most prolific and resistant to elevated temperatures, and therefore that any temperature found to be lethal for *Mytilus edulis* would also prove to be fatal for the others. Accordingly, further experimentation to determine the effect of temperature and time of exposure was confined to this mussel as it was abundant and convenient.

The result of the laboratory work is shown in Fig. 3. The curve indicates that this mussel can survive indefinitely at temperatures below 77 F. However, at temperatures above 82 F, survival is dependent upon the time of exposure and, after a temperature of 100 F is reached, the mussel dies within 1 hr.

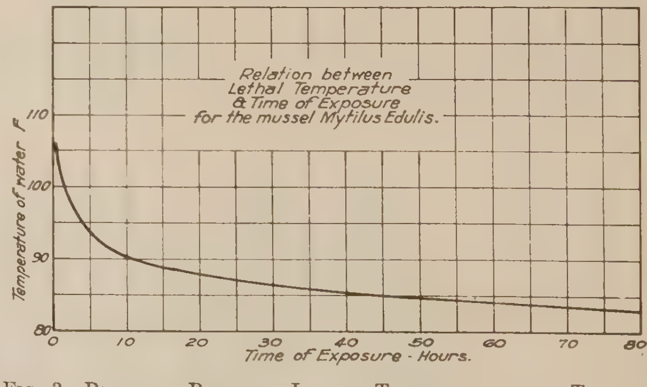

FIG. 3 RELATION BETWEEN LETHAL TEMPERATURE AND TIME OF EXPOSURE FOR THE MUSSEL, MYTILUS EDULIS

The reproductive cycle of this mussel practically ceases during the winter months when the ocean temperature drops below 60 F, and new mussels do not appear in troublesome numbers until the water temperature increases beyond 60 F in the late spring. Accordingly, it is believed that little or no treatment will be required during the winter dormant period. Conclusive evidence on this point will not be available until further experience with the system has been obtained.

The information in Fig. 3 is applied to the problem of keeping the pipes free of marine organisms in the following way: During the months when the ocean water exceeds 60 F, the gate positions are reversed periodically, causing a reversal of flow in the two lines so that the line which acted as the intake line becomes the discharge line. As soon as this happens, the temperature of water in the line increases about 19 deg F if full load is being carried in the plant. Depending upon the ocean-water temperature, this is increased further by opening one of the gates partially to cause recirculation of the water to the condenser until the temperature of the water flowing in the discharge pipe is raised to about 102 F. As shown on the curve in Fig. 3, the mussels cannot survive this temperature for longer than 1 hr. To make certain that all mussels and other growths are killed, it has been the practice, during the first summer season that this method has been tried, to maintain this temperature for 4 hours before restoring the gate to normal position and stopping recirculation.

The function of the pipes has been reversed and the temperature of the water increased as just mentioned at varying intervals from 10 days to 3 weeks. It appears that once every 3 weeks may be sufficient and, as later experience with this method develops, it may be possible to increase the length of the interval between flow reversals.

## RESULTS

During the summer of 1948 the pipes and terminal structures were treated as outlined, and during this time they remained completely free of any fouling organisms. To check upon the effectiveness of the method, a diver was employed to examine the interior of the pipes and terminal structures at least once a month and oftener during the initial phases of the operation. Also, removable concrete test panels about 1 ft × 3 ft were hung in the pipes to provide a spot sample for any growths which might have accumulated. These were removed periodically for examination above water, and likewise were found to be free of troublesome growths throughout the first summer period.

Effectiveness of the method also has been demonstrated in another way. Referring to Fig. 1, in the pump intake chamber there are located, in addition to the main circulator pumps, several small vertical pumps used for station salt-water service. During the latter part of the first summer's operation, it was necessary to raise these for internal inspection, and it was found at that time that the external surface of the pump columns carried a layer of mussels about 6 to 8 in. thick below the water line. The water surrounding these pumps does not receive the full heat-treatment given to the main conduits, and therefore the mussels are not killed periodically but flourish instead in their unmolested environment. It is reasonable to expect that growths of similar magnitude might have accumulated in the main conduits during the same period had not the treatment described in the foregoing been used.

## COST OF TREATMENT

The operating cost of the treatment is relatively small when the benefits derived are evaluated with it. It is also small when compared to the alternative method of using chlorine in lethal quantities to perform the same service. No exact data are available for the latter method because, so far, it has not been necessary to employ the method. However, an estimate has been made of the probable cost of using chlorine rather than heat and is reported here for comparison.

During the 4-hr period when the water temperature is elevated artificially at the expense of condenser vacuum and, consequently, fuel cost, the vacuum drops approximately 1 in. Hg. On an annual basis, it is estimated that the heat-treatment costs about $800 for the two 66,000-kw turbine generators presently installed. Based upon the best available estimates rather than the actual use of chlorine to accomplish the same results, if such were possible, it is expected that the annual cost of chlorine would be about $50,000.

While it is true that some additional capital expenditure was necessary to provide the facilities for reversing the flow of water periodically, it is judged that the fixed charges on these are considerably below the annual expense for chlorine as just estimated.

## CONCLUSION

A system has been devised for controlling the troublesome growth of marine organisms in two concrete ocean-water conduits by elevating the temperature of the discharge water periodically for short periods to a value slightly in excess of 100 F. The scheme has worked well during the first year of plant operation and has done so at a cost believed to be much lower than with the use of chlorine.

# Symposium on Marine Fouling—Discussion

THE following discussion is a composite of that given in connection with the symposium of papers on the subject of Marine Fouling which appears in this issue of the Transactions. References to individual papers of the Symposium will be given by numbers in parentheses as indicated in the following list, which also includes paper numbers.

1 "Some Biological Fundamentals of Marine Fouling," by W. F. Clapp, pages 101–107.

2 "Project Study for the Mitigation of Marine Fouling," by I. A. Patten, pages 109–115.

3 "Control of Marine Fouling in Sea-Water Conduits Including Exploratory Tests on Killing Shelled Mussels," by H. E. White, pages 117–126.

4 "Thermal Control of Marine Fouling at Redondo Steam Station of the Southern California Edison Company," by W. L. Chadwick, F. S. Clark, and D. L. Fox, pages 127–131.

## DISCUSSION OF PAPERS

HELEN I. BATTLE.[1] The data presented in this symposium offer a definite contribution to the immediate problem of marine fouling and are particularly enlightening to the biologist as an indication of the paucity of specific knowledge regarding the thermal-tolerance ranges of many common organisms.

The possibility of the destruction of larvae prior to or immediately on settling would involve another type of approach to the problem, namely, an accurate determination for any given locality of the following:

1 Spawning characteristics of the adult.

2 Lethal temperatures and critical temperatures for duration of chlorination of the early larva (*trochophore*), straight hinge (*prodissoconch*) and calcareous shell stage of young (*dissoconch*).

3 Preparation of prediction curves for the actual settling time under any given temperature range.

Spawning in *Mytilus* is intermittent and varies considerably in different localities. For example, Fox[2] found a simultaneous nonperiodic spawning of *Mytilus* at Alexandria and Suez to which temperature apparently had no relationship. Battle,[3] for the Fundy area, observed maximum spawning during the summer months at the time of first-quarter neaps, full-moon springs, and third-quarter neap tides, and suggested that spawning might be initiated by increased temperature of the littoral zone when the low water of the first-quarter neaps occurs during the midday. At Wood's Hole, spawning is usual from June to September, at Plymouth, England, from January to May, and in North Wales, in July.[4] Dr. Clapp (1) has drawn attention to an apparently unusual spawning in December to February, off Portland and Atlantic Beach. Nelson[5] placed a critical spawning temperature for *Mytilus* at 10–12 C. Miller[6] found a minimum temperature of 11–13 C required to initiate spawning at Bideford, P. E. I.

A determination of lethal temperatures and critical temperatures for duration of chlorination of the larval, straight hinge, and young would lend itself readily to laboratory procedure. The eggs either can be fertilized in the laboratory and the young reared successfully on cultured diatoms, or can be obtained in plankton tows with No. 18 bolting silk net. Although it might be expected that the larvae will, in general, be more sensitive to unfavorable environmental factors than the young with shells, this cannot be taken as a generalization, and it would be necessary to determine the thermal death point experimentally.

Dr. J. C. Medcof[7] has compiled composite curves for the prediction of oyster sets from growth-increment data at various constant temperatures. Such prediction curves would be of the greatest value in the instance of *Mytilus*. Conceivably, in certain localities, *Mytilus* will be subjected to a considerably greater temperature range than that of oysters, hence this will affect the duration of the free-swimming stage and present difficulties in the prediction of the actual settling time.

Further experimental work might be directed along the line of chemical control, possibly by the use of substances to dissolve or destroy the attachment of the byssus thread and not necessarily toxic to the organisms themselves. Such substances, no doubt would bring in the problems of upsetting the balance in nature since the effect might be widespread following their discharge into open water.

C. E. BLAIS.[8] Paper (4) covering the control of marine fouling by temperature at the Redondo Steam Station is an excellent presentation of the basic treatment successfully carried out on a large-plant scale at this important public-utility station.

The planning, construction, and successful operation of the elevated heat-control method thus established brings into sharp focus the value of this system as compared to some of the other control methods which previously have been suggested and installed for preventing the settling of lava forms and the killing of adult forms of fouling organisms.

The fouling of both fresh and salt-water circulating systems is a common problem to many utility and industrial plants whether they be located on the Atlantic or the Pacific seaboards. The most prevalent source of trouble appears to be caused by those fouling organisms that are members of the *Phylum mollusca*, which includes the snails and other single-shelled *Gastropoda;* and clams, oysters, mussels, and other bivalves that are most troublesome. The *Mytilus edulis* identified as the black mussel on the Atlantic Coast and a similar bivalve that is closely related, known as the *Mytilus californianus*, common on the Pacific Coast, is the most common fouling mollusk throughout the world.

Control methods previously suggested and tried have been numerous, and today, due to the untiring efforts on the part of many eminent biologists and designing and operating engineers, the problem of control can be solved effectively. It is interesting to note that the design of the Redondo Steam Station's marine-fouling-control system was predicated on the two most popular known methods of combating the fouling of salt-water circulating systems: (*a*) The heating and the recirculating of circulating water, one of the earliest schemes used on a large-plant control system; (*b*) chlorination control, probably the most extensively applied of all controlling systems in use today.

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[1] Associate Professor, Department of Zoology and Applied Biology, University of Western Ontario, London, Canada.

[2] "Lunar Periodicity in Reproduction," by H. Munro Fox, Proceedings of the Royal Society of London, series B, vol. 95, 1924, pp. 523–550.

[3] "Rhythmic Sexual Maturity and Spawning of Certain Bivalve-Molluscs," by Helen I. Battle, Contributions to *Canadian Biology and Fisheries*, vol. 7, 1932, pp. 257–276.

[4] "Mytilus," by K. White, LMBC Memoirs, March, 1937.

[5] "On the Distribution of Critical Temperatures for Spawning and for Ciliary Activity in Bi-Valve Molluscs," by T. C. Nelson, *Science*, vol. 67, 1928, pp. 220–221.

[6] "The Larval Development of *Mytilus edulis*, L," by M. M. Miller, Unpublished Report, Fisheries Research Board of Canada, 1940.

[7] "Larval Life of the Oyster (*Ostrea virginica*) in Bideford River," by J. C. Medcof, *Journal of the Fisheries Research Board of Canada*, vol. 4, 1939, pp.287–301.

[8] Chief Engineer, PWD Power Plants, Quonset Naval Air Station, Quonset Point, R. I.

The design of the circulatory structure for the Redondo Station is novel and yet not radical. It does, however, contain certain features of much interest to future designers and operators of control installations. Of primary interest is the considered effort to construct, without in any manner interfering with or detracting from the natural recreational area, this necessary facility which otherwise might interfere with the future use of the beach by the public. The engineers are to be commended for the excellence of design, and the ultimate installation which so effectively overcame local difficulties.

The writer concurs with the type of control provided for combating effectively the fouling of the circulating-water lines. The system provides for control by elevated temperatures for primary elimination, and with chlorine injection as a safeguard or for secondary defouling and is worthy of mention. Even though complete and satisfactory results were achieved without the use of chlorine during the first year's run, it is quite within the realm of possibility that this method of prevention might be utilized if future conditions warrant. Experience in the Narragansett Bay area has shown considerable variation in the variety, volume, and the rate of growth of fouling organisms from year to year in any one part of the bay. It is therefore possible that the relatively short period upon which the report is based may not be entirely conclusive as to results.

The operating cost of the treatment for the first year of operation is exceptionally low considering the benefits resulting. A complete breakdown of the cost of the installation of the terminal structure, piping and pumping station would have been quite useful for comparative purposes with other installations, particularly for use in other contemplated studies made for the purpose of determining the specific type of equipment best fitted for the complete elimination of marine fouling in other areas.

The NAS main power plant at Quonset Point was designed and constructed during the duress of the last world war. A pumping station was constructed along the bulkhead south of the main plant, and no control equipment for marine fouling was installed in the initial building unit. The power plant was not long in operation, however, before it became apparent that the infiltration of bay mussels would affect seriously the operation of the turbogenerators. Within the first year of operation, serious clogging of the pump well and large intake and fouling of the condensers necessitated outages at opportune moments to facilitate the defouling of the condenser water boxes, tube sheets, pipes, and pump well. The matter of establishing a satisfactory control was given the highest priority. A survey of the physical features of the cooling-water system indicated that the close and compact arrangement of the prime operating equipment would preclude the possibility of installing the necessary piping for control of marine fouling by temperature. The survey, however, did bring to light the simplicity and feasibility of installing a complete chlorinating system that effectively would control the marine-fouling growth of bay mussels within the system.

An automatic vacuum chlorinator was procured and installed in the pumping station. Chlorine was injected on the lee side of the sluice operating gate before the rotary screen. The chlorinator was placed on automatic control for continuous operation during the warm-weather months, with the chlorine residual maintained at 1 ppm. During the early spring and early fall months up to about October 1, intermittent operation gives satisfactory results. During these periods, the residual is maintained at 0.5 ppm. This system of control treatment has continued to be effective and extremely flexible in meeting the widely varying conditions, and the operation and maintenance are relatively inexpensive.

Louis Elliott.[9] While a steam plant is not as closely tied to nature as is a hydroelectric, there are still a number of reconciliations to make, of which the supply and handling of condensing water call for one of the most important. This condition obtains whether the station has an ocean, a lake, or a river to draw on for direct condensing, or whether in a dry country cooling towers must be used, with make-up from wells or other source.

The design adopted at the Redondo Station (4), with two 10-ft pipes laid under the sea bottom 1900 ft out from the shore, must presuppose a reasonably stable bottom—not subject to serious change of contour from waves and tides.

The paper (4) brings out the complications arising in a design of this kind—unexpected to one who has not tackled a similar problem. The 10-ft-diam pipes, to carry 400 cfs, give a moderate water velocity, e.g., 5.4 fps. This matter of pipe size was doubtless worked out with care, taking into account investment and fixed charges as against energy losses through friction, and complications arising from variation in head under various phases of operation.

Doubtless, also, the economics as to régime of changes in circulation have been worked out, taking into account necessities of temperature level to kill the mussels, loss of fuel resulting from higher water temperatures, and other elements.

Small-scale examples of similar conditions may be cited. At small steam plants on the Isthmus of Panama, difficulty arises from marine growths inside small pipes taking water from the ocean. These become clogged with mussels and other growths, in spite of the fact that according to Fig. 3 of the paper, the particular mussels encountered at Redondo would have been killed by the temperatures existing in these tropical waters. It is probable that the particular marine growths encountered at Panama are immune to the effect of temperatures that would kill *Mytilus edulis*.

Although no formal research has been conducted, certain approximate results may be compared with conditions in the north (3, 4).

South Avenue steam plant at Panama City has a capability of about 12 mw. There is an unusual condensing-water arrangement, worked out because of the wide shelving beach at the plant site, with the water receding a long distance from the plant at low tide. Circulating water is taken from the sea when the tide is high, and sufficient water is impounded in a basin to supply the cooling needs when the tide recedes beyond the suction line of the pumps. The storage basin is divided into two compartments, permitting certain control of circulation. Some surface cooling is effected during the period when tide is out.

Sea-water temperatures range from 70 F up, and condenser-inlet temperatures from 70 to over 110 F. Fouling by marine growths of pipes and other condensing-water works is experienced, particularly during the spring and early summer. This fouling has been minimized by heating the circulating water for brief periods. Arrangement can be made, daily if necessary, to raise water temperature to 115 F for a period of 20 to 30 min. This has been found effective in killing a great portion of the marine growth.

Data from southern California indicate that exposure of the mussels to 106 F kills them in 20 min. Corresponding data taken at Lynn shows a much longer time for killing all mussels with water at 105 F, and something over an hour with water at 115 F. As just stated, it has been determined at Panama that it is desirable to carry the water up to 115 F for approximately half an hour. Because of the more general character of information from Panama no close comparison can be made with Redondo and Lynn.

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A new plant under design for Panama takes advantage of this utilization of high temperatures, without use of chemicals, for killing marine growth. In this case, as at the South Avenue plant, there is to be a recirculation of warm water, 115 F maximum, through circulating-water conduits and condenser.

The circulating system for the new plant will have a siphon-type conduit 42 in. diam and 500 ft long, supplying water to the intake chamber of the circulating pumps at all stages of tide. This utilization of siphon action, permitting the placing of the intake chamber back on the shore in a protected location, has been made in a number of plants in Central and South America. At the new Panama station, a 12-in. recirculating line from the condenser discharge carries warm water, when required, to the pump-intake chamber and also to the intake siphon. The latter may be valved off, reversing the flow during the periods when high tide floods the intake chamber and the siphon feed is not required. Piping and valves are so arranged that flow can be reversed in each pass of the two-pass condenser, and any part of the circulating system subjected to a higher water temperature to kill mussels or other marine growth.

V. F. Estcourt.[10] Although the effect of increased temperature in reducing the ability of mussels to remain attached to intake conduits has been known for many years, the experimental data which have been developed by the authors (4), demonstrating a definite correlation between time of exposure and various water temperatures beyond which specific types of mussels can survive or remain attached, is extremely valuable. This information should prove helpful in designing salt-water condensing systems in power plants for minimum trouble from this type of marine growth. Although the paper (4) relates to what was done to prevent such marine growth in a specific installation, it would appear appropriate to include in this discussion a few observations relative to the basic factors which enter into the problem.

Dr. Clapp (1) adequately describes some valuable research which has been conducted in connection with the chlorination of mussels, and H. E. White (3) correlates the effect of chlorination at different water temperatures in terms of the time required to kill the mussels. None of these papers is concerned with the influence of the basic layout of the salt-water intake system upon the economic application of other methods of control. Therefore some comments regarding this aspect of the problem may be helpful in suggesting a means of evaluating the various possible solutions in terms of how much capital investment can be justified economically for the various methods of control.

The control of marine fouling from the power-plant operator's viewpoint has as its objective the elimination of trouble from restrictions in the flow of cooling water in the various conduits and piping systems, and through the main condensers and other heat exchangers, resulting from the accumulation of mussels, and other fouling organisms at the tube inlets. Four important methods of control have been known for a number of years, i.e., (*a*) properly located revolving screens, (*b*) predetermined periodic increments in water velocity, (*c*) chlorination, (*d*) predetermined periodic increments in water temperature. Each of these methods is known to be effective in varying degrees, depending upon various local conditions and also upon whether one is used to the exclusion of the other three, or whether some optimum combination of two or more methods is applied. In so far as we are aware, the use of elevated temperatures prior to the Redondo job had been confined to the process of increasing water velocities periodically, particularly during seasonal high water temperatures; and the effect of chlorination as a means of control had been somewhat inconclusive until the more recent tests at the Lynn Gas and Electric plant were completed (3).

Experience during the past 25 years in the San Francisco Bay area with salt-water cooling systems has indicated that the location of the screens in the intake system is a fundamental factor with respect to operating difficulties which will be encountered from fouling. We have examined intake tunnels up to the location of the revolving screens after many years of continuous operation and find that the accumulation of mussels on the walls of this section of conduit reaches a point of saturation which is determined by the apparent inability of the mussels under existing water velocities and temperatures to maintain a firm hold beyond a certain thickness. Although they may hang down in streamers for a while, eventually they will drop off and are then caught by the revolving screens. It is therefore extremely desirable to locate both the circulating pumps and the screens as close to the condenser as possible. What happens when there are large low-velocity conduits between the screens and the condenser is well illustrated in the paper by I. A. Patten (2).

In most instances there is little to fear from mussel accumulation in the intake conduits up to the point where the revolving screens are located. Absolutely no interruptions or curtailments of operation have resulted from mussel acccumulations in this section of the intake tunnel in any of our San Francisco Bay area plants. However, as the authors point out, there were special considerations at Redondo which made it desirable to go to the expense of controlling marine growth in the unusually long intake conduits before the screens. They do not state specifically that smaller conduit cross sections were used in anticipation of an improved roughness factor, and larger effective cross-sectional area due to the absence of mussels. Sometimes other considerations dictate the economic size of the conduit, but it would be of interest to know whether there was any saving in reduced conduit sizes at the Redondo job due to mussel control.

On the other hand, there is a much greater fouling hazard in the section of tunnel or piping between the intake screens and the condensers. It is our understanding that the original design at Redondo for the control of temperature in the intake conduits up to the revolving screens has been extended in its application to the lengths of pipe between the screens and the condensers, in order to meet the problem which usually exists in these sections of conduit which are unprotected by screens. It would be of considerable interest if the authors (4) would describe the results obtained at this point in the system that is, between the circulating pumps and the condensers.

At our Moss Landing steam plant, because there were physical restrictions which made it difficult to bring the revolving screens close enough to the condenser, we not only have manifolded the individual circulating-water-pump discharges, but have arranged the condenser piping so that some or all of the water can be returned in reverse direction through one half of the condenser, thence continuing in reverse direction through one of the pump-discharge lines, thereby elevating the temperature of the cooling water and taking advantage of both increased temperature and velocity, if necessary, in order to remove any mussel accumulations. Had it been economically feasible to locate the revolving screens and pumps within, say, 25 ft or 50 ft of the condensers, these provisions probably would not have been necessary. Full reliance is being placed upon the ability of the revolving screens to prevent any trouble from mussel accumulations in the section of conduit up to this point.

This subject would not be complete without mentioning the special problem which sometimes develops in small salt-water pipes of, say, 3 in. diam or less. Mussels have been known to grow in these small lines until they are almost completely plugged. This has been eliminated in some instances by the substitution of heavy rubber hose and rubber-lined fittings. Apparently the mussels have difficulty in attaching themselves to rubber, and it would appear that the valuable investigations described in the papers of this Symposium might well be extended to include a further study with respect to the effect upon mussel accumulations of special linings and coatings on the inner surfaces of salt-water conduits.

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[10] Engineer of Steam Operation, Pacific Gas & Electric Company, San Francisco, Calif. Mem. ASME.

Gustave Heinemann.[11] At Corpus Christi plant of the writer's company, large volumes of sea water are used for process-cooling. Although it was planned to commence chlorination of the sea water at the time operations began in 1934, some delays were encountered in the installation of the chlorination equipment. This resulted in our operating the plant for several months with unchlorinated sea water before a chlorination program could be started. Drawing on the experience reported by others, in which it was claimed that shelled mussels could be killed after several days continuous chlorination, it was decided to chlorinate the water on a continuous basis, maintaining chlorine residual roughly 0.5–1.0 ppm for 4 days prior to commencing an intermittent chlorination program. At the end of the 4-day period the lines were flushed, resulting in the recovery of tremendous quantities of killed mussels. Although careful inspection of the lines was not possible, there were definite indications that the kill was essentially complete.

Following the initial continuous treatment, varying programs of intermittent chlorination were tried from 20 min each 8 hr to 40 min each 2 hr. Experimentation indicated that the latter heavier schedule appeared to be necessary for effective control in these waters. With a program of 40-min chlorination each 2 hr, and a residual approximating 0.5–1.5 ppm, essentially complete control is obtained. This experience has also been confirmed by a power plant in this area operating on water from the same source.

It appears evident that in any discussion of mussel control, a consideration of local conditions is of extreme importance. For example, H. E. White (3) shows that with mussels from Lynn Harbor, a complete kill is obtained at temperatures less than 85 F even without the use of any chlorine. W. L. Chadwick, F. S. Clark, and D. L. Fox (4) state that mussels in the Redondo Beach area of California are killed after the temperature of the water reaches 82 F. The growth of the mussels in the Texas Gulf Coast waters is extremely prolific, even during periods when the water temperature is as high as 90 F. This would indicate that the curves which have been presented cannot be applied to normally warm waters such as those in this area.

During the winter season when the water temperature is as low as approximately 60 F, and occasionally as low as 50 F, the rate of mussel growth is decreased tremendously. During the summer season, representing at least 4 or 5 months of the year when the water temperature will be in excess of 80 F, the rate of growth is very rapid. This would indicate that the mussels in this area will withstand temperatures considerably in excess of those at Lynn Harbor or at Redondo Beach.

We do not have any experience to show the effect of temperature on the length of time necessary to kill shelled mussels from waters in this area at varying temperatures using chlorination. Our experience along this line is confined principally to continuous chlorination for 3 to 4-day intervals, such as was employed when chlorination was first begun, and at times when the water temperatures were in excess of 80 F.

It would appear desirable that further work be instituted to determine the length of time necessary to kill Gulf Coast mussels with chlorine under lower temperature conditions. It also would appear desirable that work be instituted to determine the thermal death temperature of these mussels under varying times of exposure.

B. G. Hume.[12] Marine fouling of circulating-water systems of steam plants on the West Coast has been particularly aggravating to the operating personnel. More trouble has been experienced from marine growth in plants located on open water, where fresh clean sea water is available, than in those located in harbors. Mussels in particular seem to like clean water. Undesirable as it is to have the circulating water contaminated with industrial wastes from a corrosion standpoint, it does discourage the growth of mussels and some other forms of marine life. Mussels are the most objectionable, as they break off from the tunnel walls, and frequently plug the condenser tubes completely or, worse still, lodge inside and cause tube failure from cavitation.

It has been found that chemical control of the circulating water is either too expensive or inadequate to prevent the growth of the more vigorous types of marine life. Therefore it has been necessary to resort to the very expensive method of cleaning tunnels by hand anywhere from one to three times a year. Chemical control still proves to be adequate and quite necessary to prevent the growth of the slimes that are so detrimental to a good heat-transfer rate in condensers, but the mussels protected by shells are highly resistant to chemicals.

The Department of Water and Power of Los Angeles Harbor steam plant uses water from the Los Angeles Harbor. The intake tunnels are about 1200 ft long, and no difficulty has been experienced from marine fouling during the 7 years these tunnels have been in use. In fact, they have been cleaned only once during this time. The sea water in the vicinity of the Seal Beach steam plant, however, is practically free from industrial contamination, hence considerable trouble is experienced with growth of marine life in the intake tunnels.

Mussels grow in great abundance in the inlet tunnels of this latter plant. They hang in festoons on tunnel walls, inlet pipes, and condenser water boxes. As this plant is now being used for hot stand-by service and is generally shut down over week ends, attempts have been made to discourage the growth of mussels. This was done by injecting chlorine solution into the intake tunnels just before the week-end shutdown, thereby subjecting the growth therein to a "soaking," in water having a residual chlorine content of 2 to 4 ppm.

This procedure has failed to rid the tunnels of mussels, as they apparently close up tightly when the chlorine solution surrounds them and then open up when the danger has passed. Ordinary periodic chlorination for slime control seems to have little or no effect on them.

In designing the extension to the Seal Beach steam plant, the Department proposes to make use of the principles of recirculation in a slightly different manner from those adopted at Redondo. It is proposed that circulating water for the future units at Seal Beach will be taken from Alamitos Bay, as at present, by means of twin 8-ft-diam precast concrete tunnels and discharged to the San Gabriel River. When it is desired to raise the temperature of the water in the tunnels, a portion of the warm circulating water from the condensers will be discharged into one of the intake tunnels. By means of gates, the flow of water will be reversed in this tunnel and warm water will flow toward the intake structure where it will be recirculated and drawn into the other tunnel, and back into the condenser again. It is anticipated this reversal of flow will be done during week ends or other periods of light loads where one tunnel can be spared. In this fashion, the quantity of warm water recirculated can be varied, and the temperature of the water can be controlled to any desired degree. This scheme will permit raising the temperature of the water in the whole circulating-water system sufficiently to kill the marine life, thereby eliminating any parts of the system in which mussels could develop, break away, and get into the condenser tubes, causing tube failure.

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The method of preventing growth in tunnels by raising periodically the temperature of the water to 100 F or thereabouts for a few hours, appears to be the answer to a very troublesome problem in this area. Those responsible for initiating and carrying out this very expensive and elaborate experimental work should be highly commended for their part in advancing the art of power-plant design and operation.

L. W. Hutchins.[13] The four papers of this Symposium provide a balanced, up-to-date account of most of the aspects of intake-tunnel fouling which are of practical importance, ranging from biological fundamentals to the two cases of plant-scale control.

The very rapid accumulation of fouling in intake tunnels and associated circulating systems is mentioned by several of the authors. Calculations show that the rate of growth in the Lynn tunnel in at least 2 years has exceeded the prodigious figure of 1000 tons per acre of surface per year. No figures remotely comparable are known to biologists from any other sources; thus under the most favorable conditions with the most productive crops, the best farm yields are only of the order of 10 tons per acre per year, for example. From our investigations in the Lynn tunnel, it appears both that the occurrence of large numbers of organisms and the growth of the individuals at unusually rapid rates are factors in the rate of accumulation of that fouling. On the one hand, as many as 6000 mussels have been found on a square foot of wall in the Lynn tunnel. Again, while Dr. Clapp (1) mentions a length of 50 mm being reached after 10 months, a figure which many authorities approximate as normal, in the Lynn tunnel this size may be reached after as little as 17 or 20 weeks.

Most of the common enemies of mussels are excluded from tunnels such as that at Lynn by the trash racks and screens, and probably this is responsible to an important degree for the large numbers of mussels occurring there. Darkness, continuous submergence, reasonably high salinities, adequate oxygen, moderate currents, and sufficient food are all factors which appear to promote mussel growth. It is obvious that an intake tunnel commonly will provide an ideal combination of these, which suggests an explanation of the rapid growth of the individual mussels. An intake tunnel, in short, is probably as close to a perfect environment for mussels as it would be possible to get.

Chlorination has certain effects on mussel growth which perhaps are worth mentioning. Measurements of several thousand mussels from the Lynn tunnel collected at various times over the last 5 years show conclusively that mussels subjected to chlorination are relatively fatter than those growing in unchlorinated water. The concentration of chlorine appears to have no effect in this connection, but the effect becomes more pronounced in mussels subjected to longer treatments in a given period, and it is most extreme in mussels subjected to continuous chlorination. With intermittent treatments of very short bursts, such as the 20 min per 8-hr shift used in 1946, there is no killing and the over-all growth rate does not appear to be reduced. The result, therefore, due to the slight fattening induced by the chlorination, is to increase the actual bulk of fouling for equivalent numbers of mussels. Chlorination in short treatments thus not only achieves no control, but is actually detrimental in developing a larger bulk of fouling. This seems not to have been known previously.

All of the evidence now available indicates that chlorination, to be an effective control method, must be used in long doses. If intermittent chlorination is desired or necessary, as might be the case in a reversing tunnel system, the schedule apparently should be something on the order of a month on and a month off, rather than a short phase alternation.

Dr. Clapp's demonstration of mussel attachments on test panels at Atlantic Beach in midwinter shows that it is not entirely safe to schedule control methods only for normal fouling seasons. Usually, of course, it is the summer which is the critical time of year for fouling attachment, particularly in the temperate waters where *Mytilus edulis* is involved. Freak off-season sets do occur occasionally, however, and plants should be prepared to employ control methods at any time of year should inspection show that such an unusual set is taking place. It is essential to keep a continuous systematic watch over all installations and not to rely entirely on normal or average data about fouling seasons.

This is especially important in such an installation as the Redondo plant, where the tunnels cannot be cleaned manually and where, therefore, every possible precaution must be taken to maintain them in a clean condition. In this connection it may be noted that while the heavy set of mussels in the Redondo area normally does occur between spring and fall, some mussels are known to breed throughout the year.

Small-scale experiments or laboratory tests are always artificial to some degree and seldom if ever duplicate exactly the conditions obtaining in actual installations or in other tests. Discrepancies are to be expected, therefore, in comparing data from various sources, and it will be noted that there are some in these papers concerning the durations of exposure which are fatal at various temperatures for *Mytilus edulis.*

Thus the data in Mr. White's Fig. 5 (3) do not indicate that the Redondo treatment of 4 hr at 102 F would be adequate, nor do they support Ritchie's earlier use of 12 hr at 90 F at the Edinburgh Westbank Station, although satisfactory control seems to have been obtained at both plants. The differences are minor, however, and do not affect the general concept of control by heat.

Nearly all tests agree in indicating a critical temperature for *Mytilus edulis* in the vicinity of 84 F. Comparatively brief exposures to temperatures higher than this are fatal, while at temperatures below 84 F killing is achieved only by very much longer exposures or not at all. This agrees very closely with what can be inferred from the geographical distribution of *Mytilus edulis.* The southern limit of the species on all coasts throughout the world occurs just about where water temperatures in the hottest part of the summer can be expected to exceed 85 F for several days. Penetration of the species further into the tropics, in other words, would take it into water whose summer temperatures would be lethal. It is possible to make similar inferences about critical temperatures for many other fouling species from their geographical distributions.

Because the economics of fouling control have been debated widely with relatively little evidence, it is valuable to have two further cases in which control has been obtained economically. The Lynn case demonstrates that fouling dominated by *Mytilus edulis*, along with condenser sliming, can be controlled by continuous chlorination at a net saving to the company relative to the cost of maintenance and the less efficient operation without fouling control. The Redondo case provides a similar demonstration for the high-temperature method, although this is limited to the gross fouling and does not control sliming.

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Since there has been considerable doubt of the practicality of fouling control by heat, the Redondo case is also interesting for the very close duplication and confirmation it affords of the experience at the Edinburgh Westbank station reported by Ritchie. Relative costs of chlorination and heat-treatment cannot be determined solely from the Lynn and Redondo data as given, since neither includes figures for equipment, fixed charges on investment, etc., as well as because only one controls sliming. The Redondo estimates for chlorination there, however, seem high compared to the Lynn costs; solely on the basis of volumes of water handled, the Redondo cost estimate should not exceed about $15,000 per year at present.

In any event, a final evaluation of the two methods cannot be obtained from only 1 or 2 years' experience at one or two installations; it is to be hoped that further reports on these plants will be forthcoming after the control methods have been in operation several years, and that additional data will be contributed by other units. Meanwhile, all who are concerned with this problem of fouling in circulating-water systems will be indebted to the present authors for their discussions of their experience.

F. L. LaQue.[14] It is evident that the attention being given the control of fouling in intake tunnels by the authors of papers (3) and (4) is providing a good technical basis for future progress.

At our Marine Test Station at the Ethyl Dow Chemical Company plant, Kure Beach, N. C., we have had opportunity to observe the growth of mussels under conditions which emphasize a point which is indicated also by a comparison of the results obtained in paper (3) as compared with those in paper (4). This point is that the heat that mussels can withstand is likely to be determined to a great extent by what they are accustomed to in their normal environment.

For example, the mussels exposed to the sun between tides on a steel bulkhead at Kure Beach are certainly able to survive combinations of time and temperature which the data of Chadwick, et al, indicate should kill them. Similarly, mussels there have survived the high temperature reached inside the upper surface of a partially buried $^3/_8$-in-thick black steel pipe line which regularly remained full of stagnant sea water during daylight hours when pumps were not operated. Finally, the sea water itself at Kure Beach reaches temperatures during the summer months that may average 83 F with occasional peaks of 86 F. The only effect on the mussels appears to be to stimulate their growth instead of killing them in 80 hours or so, as indicated in Fig. 3 of the Chadwick paper (4).

Perhaps the absolute temperature is not as important as the extent and rate of increase in temperature above normal in determining the killing effect.

All this means, of course, is that the heat-treatment required to kill mussels will have to be established for each location, and results secured at any plant cannot be used as more than a rough guide as to what might be successful elsewhere.

Having in mind, also, the indications in Fig. 10 of Mr. White's paper (3), which show that some mussels are much hardier than others, attention might be given the possibility that the offspring of the survivors of a killing treatment in its early stages may become conditioned to it. In time, as the number of survivors increases, it may be necessary to make the killing treatment progressively more severe.

In appraising the results of tests made in the laboratory, due consideration must be given to the possibility that the laboratory environment, in a general way, may be unhealthy. The mussels in the laboratory may, therefore, be more vulnerable to destruction. On this basis, therefore, the data indicating probable life at temperatures approaching normal may reflect largely the ability of the mussels to survive in the laboratory environment. It would be prudent to assume that in practice, killing treatments may need to be more drastic than indicated by laboratory studies.

In reports of the killing effects of chlorination it is necessary to define how the determination of residual chlorine content is made. It has been discovered[15] that with sea water the common ortho-toluidine colorimetric method indicates a chlorine concentration which is about one half that shown by the standard starch-iodide method or by titration with methyl orange. For practical use of results, all that is required is that the method of measuring chlorine be defined or described so that it can be followed by anyone else.

With regard to effects of chlorination on corrosion, some recent tests at Kure Beach have shown that corrosion of 70:30 cupro-nickel alloy is reduced by continuous treatment with chlorine to a residual of 0.5 ppm (ortho-toluidine) and at water velocities up to 10 fps. Intermittent treatment with concentrations up to 3 ppm resulted in a slight increase in corrosion at the highest velocity, with the effect being greater with the longer the interruption of treatment. In general, the observations at Kure Beach, with respect both to killing effects on organisms and possible corrosion of metals, would favor continuous treatment at low chlorine concentrations (0.5 ppm ortho-toluidine) as compared with intermittent treatments at higher concentration.

R. B. Martin.[16] During informal discussion following the meeting, particular attention was directed to the exceedingly high ($50,000) estimate of annual chlorine requirements for the Redondo Steam Station (4) which appeared out of keeping with the chlorine rates and accomplishments discussed by Mr. Patten (2) for the Lynn Gas and Electric Company. The other papers and discussions also gave rise to the suggestion that moderate and economical combinations of chlorine with elevation of water temperatures to accelerate the life processes of the macroorganisms could be counted upon to produce equally good results at a probable saving in heat and in chlorine. Mention was made during the discussions of the continuing experimental work at Kure Beach, N. C., and elsewhere, wherein it is expected that extensive tests can be conducted to prove the value of combinations of low chlorine residuals and moderate elevations of temperatures.

As applied to the Redondo operating conditions, for example, the Lynn methods might call for an annual chlorine consumption for marine fouling of $6000 for the two condensers now operating, to which might be added $600 for 26 weeks of normal intermittent chlorination of the 90,000 gpm for slime control; whereas a combination of chlorination with the present use of $800 of applied heat would use not more than $70 of chlorine for the 13 annual periods of 4 hr of heating. This combination should show also some promise of alleviating the marine fouling in the pump-suction chamber, and in the discharge piping from the circulating pumps to the condenser-inlet water boxes.

S. T. Powell.[17] The growth of marine organisms in water-circulating tunnels is a serious problem in the operation of many steam-generating plants using sea water for condenser cooling. This Symposium is most timely and should influence greatly the design of the intake tunnels in stations which are to be built in the future. These problems have been encountered and their importance recognized throughout the world, and it is surprising that control procedures merely by elevation of temperature have not been more universally practiced.

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[14] In Charge, Corrosion Engineering Section, Development and Research Division, The International Nickel Company, Inc., New York, N. Y.

[15] "Corrosion of Steel Pipe by Chlorinated Sea Water at Various Velocities," by V. B. Volkening, paper presented at NACE annual meeting, Cincinnati, Ohio, April 14, 1949.

[16] Industrial Division, Wallace & Tiernan Products, Belleville, N. J.

[17] Consulting Chemical Engineer, Baltimore, Md. Fellow ASME.

As early as 1903 an attempt was made to control the marine growth in tunnels by the addition of copper sulphate. This treatment was practiced by the Cargo Fleet Iron Company Ltd. of Middlesbrough on the northeast coast of Great Britain. Some beneficial results were obtained from the use of this chemical but the results were not wholly satisfactory. Subsequently, an extensive investigation was undertaken by Dr. James Ritchie of the Royal Scottish Museum in Edinburgh.

The investigation was made to develop a procedure for preventing the growth of mussels in submarine shafts and tunnels at the Westbank Electricity Station at Portobello. The earlier work was supplemented by an investigation to develop operating procedures to prevent blocking of the Portobello tunnels by seaweed. A number of forms of chemical treatment were studied, including the use of chlorine compounds, sulphuric acid, copper sulphate, and other chemicals. Other studies were carried out concurrently to determine the value of temperature variation for the control of mussels and other marine growth adhering to the walls of the tunnels and shafts.

It is most interesting to note the similarity of the findings of the present authors, and those of Dr. Ritchie reported more than twenty years ago. The recommendations made by Dr. Ritchie as a result of his comprehensive study are presented verbatim in the following:

1 "That a reversed current or outflow of heated sea water be passed down each tunnel, and that it be passed until all the water in tunnel and shafts has attained a minimum temperature of 110 F, by which time all the mussels will have been killed.

2 "That it is unnecessary to pass such heated water daily or even weekly, but that to prevent undue development of the mussels in the tunnels the heated current be passed once every four weeks during the spatting season.

3 "That, for all practical purposes, the spatting season and the season during which douching must be continued, may be reckoned from the beginning of March until the end of October.

4 "That immediately after the first application of the above recommendations control observations be made at the grid on the end of the sea-shaft to test the efficacy of the heated overflow."

The principal difference in the findings of the two groups of investigators appears to be the top limit of the temperature requirement for prevention of the growth and development of the marine organisms. However, at the Portobello investigation, it was definitely demonstrated that the temperatures below 100 F were very effective, but the higher temperature was recommended to insure as complete control as possible. It is conceivable, also, that there are different types of organisms encountered at the Portobello Station than those at Redondo and Lynn Harbor.

It would be interesting to evaluate the efficacy of the treatment on the different organisms found at the two stations. It is recognized of course that, as the temperature to which the water heated is increased, the cost of the treatment increases, and it is obvious from the standpoint of economy that the temperature should be raised only to the point at which the efficacy of the treatment is commensurate with the increased operating cost.

The writer was interested to note that the authors of these papers have drawn attention to the fact that this form of treatment is not a substitute for control of bacterial slimes forming on condenser tubes, but the thermal treatment is a specific corrective measure for the control of shelled mussel growth. It would be interesting to evaluate the increased rate of growth of bacterial slimes resulting from the occasional increase in the temperature of the water. It is possible that the growth of bacteria responsible for slimes might increase because of the more favorable temperature of the water during the life cycle of the organisms. Other factors may be encountered because of the changing biology of organisms present in the water resulting from the elimination of the mussels.

**Lester Randall**[18] **and D. Douglass.**[19] Favorable results in the control of marine fouling by intermittent chlorination at the steam station of Stamford Gas & Electric Company were obtained January, 1942, to August, 1945. The tests relate to a 25,000-kw installation which started operation in 1942. The circulating-water pipes carrying the sea water from the pumps at the screen well are 3 ft diam and have a total length of 262 ft. The load conditions have been such that the reported velocity of 5 fps has been maintained almost continuously. The present schedule of chlorination consists of feeding 60 min per 24 hr and maintaining a residual chlorine concentration of approximately 0.5 ppm at the condenser discharge.

The amounts of marine fouling removed annually from the circulating-water pipes were as follows:

| Year | Marine fouling removed, cu ft |
|---|---|
| 1945 | 3.7 |
| 1946 | 11.2 |
| 1947 | 12.5 |
| 1948 | 6.0 |

Continued accumulation of marine fouling at rates in excess of 200 cubic feet per year in the pits where chlorine had not yet dispersed, indicates corresponding accumulations would have continued in the pipes if chlorination had not been applied. The accompanying charts, Figs. 1 and 2 on the following page, show typical water temperatures in the intake, but it should be noted that these are in excess of natural sea-water temperatures for the locality because of partial recirculation of the heated circulating water.

**G. K. Saurwein.**[20] The Cannon Street Station of the New Bedford Gas and Edison Light Company is located on tide water at the mouth of the Acushnet River on Buzzards Bay. It was built by Stone & Webster in 1916. Several extensions have been added through the years and now the station has the following installed capacity:

1 10,000-kw unit at 210 psi, 500 F temperature
2 15,000-kw units at 210 psi, 500 F temperature
2 20,000-kw units at 210 psi, 500 F temperature
1 25,000-kw units at 875 psi, 900 F temperature
1 7500-kw topping unit at 875 psi and 850 F temperature

There is currently being installed a 30,000-kw 900-psi unit.

The units now in service require about 90,000 gpm supplied through a traveling screen house and an 11-ft-wide 6-ft-high intake tunnel running the length of the powerhouse, about 450 ft, with several suction wells each about 10 ft × 18 ft. This tunnel had no gate or other means for stopping off the water, and has never been cleaned.

About 20 years ago shell material began to get into the con-

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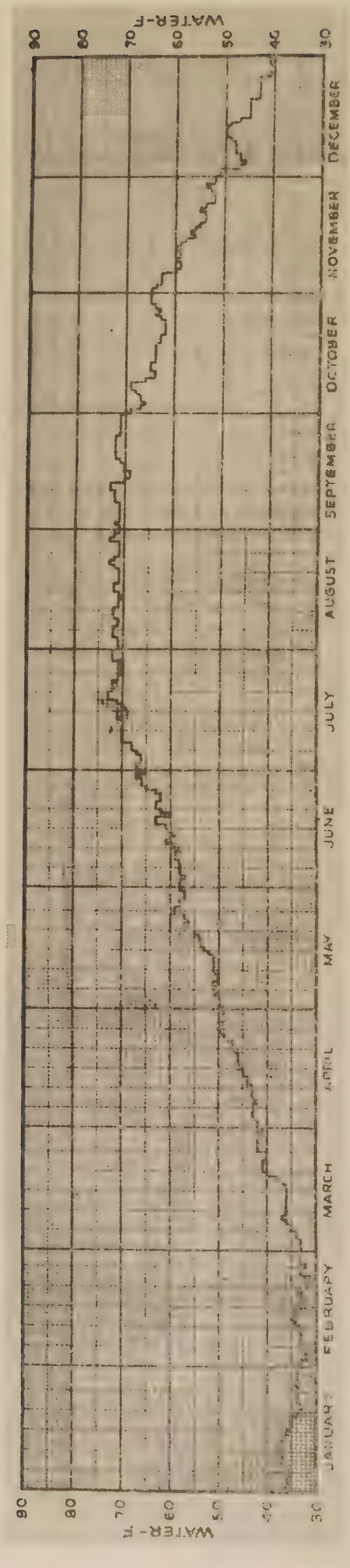

Fig. 1 Intake Water Temperatures—Daily 1946

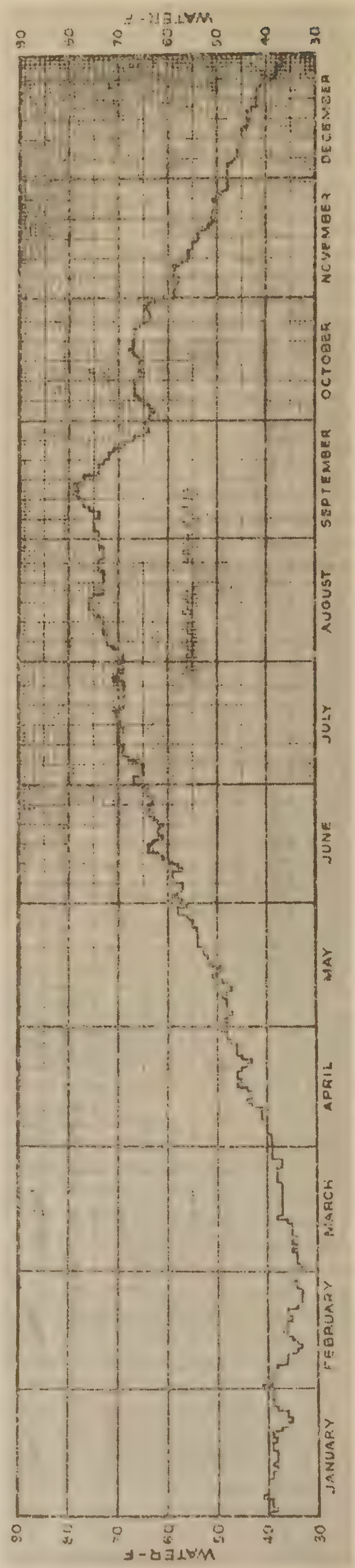

Fig. 2 Intake Water Temperatures—Daily 1947

denser water boxes requiring shutdowns for cleaning. Shell trouble varied greatly from year to year; some seasons quantities were very large, and in others almost negligible. This trouble was not very disturbing during the 1930's when there was plenty of spare capacity in the station. However, when war activity began and load increased, these interruptions were serious. In 1939 R. D. Stauffer, chief engineer of the system, conceived the idea of providing a large-size blowdown connection at the bottom of the inlet water boxes. Twenty-inch "blow-down" connections were installed on the 20,000-kw units and 16 in. on the 15,000-kw units. These cut the time of cleaning water boxes from $1^1/_2$ hr to 7 min. This of course did not remedy the tunnel condition. More shell material was continually accumulating and obstructing the flow of water. Examination by diver in 1943 showed that the sides and roof were encrusted with matted seaweed and mussel shells to a depth of 6 in., and the accumulation of material on the floor varied from 1 ft to as much as 3 ft in depth. The discharge tunnel contains none of this material.

Due to the summer population of Cape Cod, the peak load on this plant occurs during the summer months, when the water is warm, use of condensing water greatest, and activity of the mussels at a maximum. To stop condenser plugging, it is imperative that the tunnel be cleaned. Therefore it was planned to install a gate in the tunnel, and to provide auxiliary condensing-water supply to the three largest units in the plant which will carry week-end loads. The tunnel may then be shut down over one or more week ends for the cleaning operation.

Three 15,000-gpm vertical pumps have been installed and connected by concrete and cast-iron piping to the 25,000-kw and the two 20,000-kw units. These pumps are so arranged that two may serve the new 30,000-kw unit now being installed, leaving one spare pump.

An 8-in. vertical dredge pump has been provided for handling the solid material. It will be lowered into the tunnel at convenient points along its length. When the auxiliary condensing-water pumps are in service, the tunnel gate will be closed and the tunnel pumped down to a 2-ft depth of water which will be maintained for flowage of the solids to the dredge pump.

A crew will then enter the tunnel with spades, scrapers, and rakes to move the solid material to the dredge pump. The pump will discharge through a pipe line laid with dresser couplings to a collection point at the dock. About 500 cu yd of material will have to be removed from the tunnel and the pump suction pockets.

The first chlorinating equipment was installed in the plant in 1937, when a 720-lb per day unit was put in. In 1940 this was replaced by two 2000-lb per day units. This equipment controls slime well but could not remedy the mussel condition. On October 3, 1943, officials of the company met at the plant with representatives of the Wm. F. Clapp Laboratories to examine the tunnel and discuss remedies. It was suggested then that higher rates of chlorination be used to give up to 3 ppm residual at the condenser tail pipes. However, larger chlorinating equipment has not been installed to date. A plan is now being considered of light intermittent dosing of about $3^1/_2$ ppm for slime control and a heavier continuous application during the summer months for mussel control. According to the Lynn experience, continuous chlorination during the summer with a residual of only 0.25 to 0.50 ppm will be effective. After removing the accumulation of solids from the tunnel it will be possible to keep it clean.

Cost of auxiliary condensing-water installation and tunnel-cleaning equipment will approach $100,000. Cleaning operations will be reported when completed.

### CLOSURE TO PAPER (3) BY H. E. WHITE

The wide recognition of the importance of this project is evidenced by the breadth of discussion, which has significantly enhanced the value of the original papers. The specific appreciation of the background work expressed by Mr. Hume is particularly gratifying.

Dr. Battle's interesting discussion includes an outline of a rational procedure for studying the killing of mussels while very young, immediately upon arrival in an intake tunnel. Presumably, this would lead to continuous treatments at times determined by the active spawning periods. Certain of the proposals advanced might also bring improvement in existing methods of control:

1 Killing treatments for embryonic mussels can be successfully studied in the laboratory.

2 Spawning periods, although at some sites independent of water temperature, might be predictable with the aid of supplementary factors.

In case predictions were inaccurate, or unintended interruptions of the proposed treatments occurred, shelled mussels might develop and make necessary a return to types of treatment suitable for the adult form.

The possibility of destroying the mussels' attachment threads would make an interesting study, although preliminary trials were not encouraging for commercial application. The material resists long exposures to free chlorine approximating 100 ppm.

We are indebted to Mr. Elliott for extending the geographical range of observations to Panama where marine fouling organisms live at a minimum sea water temperature of 70 F, and 115 F is required for 30 minutes to give commercially acceptable control. It is striking that, where impounding basins may give temperatures of intake water exceeding 100 F during normal operation, the killing temperature may be only about 15 F higher.

Mr. Escourt's report further extends the range of data to San Francisco Bay. In that area, apparently, detached mussels are swept along the floor of the tunnel by the flowing water to the traveling screen and are there carried upward for disposal. Although somewhat similar action does occur on the East Coast with the lesser masses of small mussels, the typical thick mat in a zone ineffectively treated may merely fall to the floor and remain as a stationary obstruction. An accumulation from 1 ft to 3 ft deep of fouling debris in the tunnel at New Bedford was reported by Mr. Sauerwein. Greater depths have occurred elsewhere. Apparently, the volume of fouling carried along the tunnel to be lifted by a traveling screen would depend upon the effective water velocity and the size and effective specific gravity of the individual masses after detachment.

With reference to the use of rubber lining as a means of discouraging attachment of mussels, this might receive more detailed observation to determine the period for which the rubber surface would remain an effective retardant.

Mr. Heinemann reports that the typical winter temperature of the water at Corpus Christi is 60 F with continuing summer temperatures in excess of 80 F and that, in other Gulf Coast areas, growth of mussels is extremely prolific with natural water temperatures of 90 F. As these higher temperatures would kill mussels in the vicinity of Massachusetts in a few days, these Gulf Coast mussels obviously require higher temperatures for killing than those on the East Coast as he points out. It is also interesting that approximately complete killing is accomplished at Corpus Christi by continuous chlorination within four days at 80 F, suggesting that the resistance of mussels on the Gulf Coast to chlorination may not differ greatly from that of the mussels along the northern coast. The further studies which Mr. Heinemann suggests should add to the understanding of fouling control.

Mr. Hume's observations at Seal Beach Station on the ineffectiveness for mussel control of "soaking" chlorination over a week end and the usual intermittent chlorination for slime control are in general accord with the test curves for chlorination. For accomplishing control within week-end intervals, killing may be accelerated by temperature rise.

Dr. Hutchins concludes that short, intermittent periods of chlorination are ineffective for killing shelled mussels and that longer periods of several weeks each would be much more efficient. This thesis is thoroughly supported by observations at Lynn, but variant cases reported in the symposium include stations at Stamford, Connecticut, and at Corpus Christi, Texas, although the partial recirculation may be a factor at Stamford.

Mr. LaQue's conclusion that conditions in tunnels of power stations may differ from those in small-scale tests is substantiated by specific observations. For example, mussels may have been permitted to gather into a continuous thick mat on the walls of the tunnel before the killing treatment is applied. This diverts the main current of water and may greatly extend the time required for the treatment to take effect on the organisms closest to the surface of the wall. In this case, the treatment required in the tunnel may be considerably longer than a laboratory test on individual mussels would indicate. Notwithstanding, it may be noted that the small-scale tests are generally applicable to the treatment actually reaching the individual mussel of a mat.

Another factor which may be important is the time of travel of the water through the tunnels. For a long tunnel this might be a half hour or more at light load. During such a period, the free chlorine initially available for killing at the point of introduction might be largely consumed by the accumulated organisms on the walls before reaching the farther end of the tunnel. Again, it may be noted that the small-scale tests indicate the concentration of chlorine which must actually reach the individual mussel in the commercial installation.

Mr. LaQue suggests that the second generation of mussels may have much more resistance to a given temperature treatment than the predecessors. This is probably so. Apparently, however, it is unnecessary to wait for a second generation, as limited observations indicate resistance of a given group of mussels to a given heat-treatment may increase within a few weeks.

Mr. Martin's suggestion as to possibilities of moderate temperature increase to minimize chlorine consumption may find application where moderate recirculation is already available, as for ice control.

Mr. Powell refers to the commendable pioneering work of Dr. James Ritchie. Dr. Ritchie showed that fouling could be controlled by heating without use of chlorine. As suggested by Mr. Powell and as clearly demonstrated by the present symposium, there is a wide variation in the required duration of a given killing treatment at different sites. It was, therefore, necessary to make specific tests at Lynn and Redondo to approximate reliable control schedules. The present paper includes, in addition, charts of specific effects of temperature on chlorination and approximate comparison of chlorination with control by temperature alone.

Messrs. Randall and Douglass report continued satisfactory commercial control of marine fouling at the steam station of Stamford Gas and Electric Company while using intermittent chlorination 60 minutes per 24 hours with a residual chlorine concentration of approximately 0.5 ppm at the condenser discharge. Possibly, the temperature rise from partial recirculation outside this station simulates to a degree the results at Panama where controlled external recirculation gives effective control by temperature alone.

Mr. Sauerwein's discussion illustrates limitations which develop where peak loads occur when growth of marine fouling is at a maximum. Possibly a contributing cause of the previous ineffectiveness of chlorination at Cannon Street station was an insufficient period of treatment, particularly at the base of the thick mass of accumulated mussels.

*Economics*

Messrs. Blais, Elliott, Estcourt, Hume, Hutchins, Martin and Powell raise questions concerning the relative economic value of chlorination as compared with temperature rise alone or combinations. This was mentioned only briefly in the paper. Economic selection of treatment might be based logically on conditions at each individual station; particularly on (*a*) the steam consumption characteristics of the main turbine units, (*a*) the expected electrical load conditions, (*c*) the feasibility of reversing the flow of circulating water, and (*d*) the resistance of the local fouling organisms.

Where the temperature rise for control of marine fouling is obtained by partial recirculation of the circulating water, a reduction in vacuum on the main turbine generally occurs. For stations designed for stand-by service, the temperature rise of the circulating water through the condenser may reach approximately 20 F with no recirculation. Under these conditions the additional rise required for the desired killing treatment may be moderate. Many turbine generators recently installed are of the "preferred standard" type. As is well known, the effect of reduced vaccum on steam flow to the throttle for this type of turbine may be almost negligible at the high loads. In other words, for this particular design of turbine, under prevalent electrical loads water may be heated with very little increase in station fuel rate. For turbines of other designs and other loads, however, the costs might be considerably higher.

Where killing is desired within the minimum time from the beginning of treatment, as during a holiday shutdown, minimum elapsed time would be expected if treatment were continued until final death, as in the tests of the present paper. Where the cost of heating water is low, this may be a convenient practice. On the other hand, where heating cost is significant and time is available between treatment and delayed death, the cost of treatment may be significantly reduced, under some conditions at least, merely by reducing the duration of the treatment, as brought out by Dr. Fox.

*Test Procedure*

Dr. Hutchins and others were interested in details of test procedure used, particularly for possible comparison of reported results with those obtained by other procedures at widely separate sites. For reasons of space limitations, much detail was omitted from the original paper. The following amplifying comments may be helpful in interpreting the test procedure.

At the outset of the project the results of Dobson's[21] test were the most specific published data found for mussels in the New England area. At least approximately comparable results seemed desirable. Fundamentally Dobson's procedure was adapted to indoor manipulation by the equipment described in the present paper. The principal deviation from Dobson's procedure was that the tests were continued until all specimens were considered dead. The reason for this was the considerable increment in the length of treatment required to kill the last survivors.

Specimens were retained in the trays under treatment until all were "dead." The criterion used to determine the time of death was the time when specimens no longer responded to a sharp needle applied to the soft tissues between the reopened shells.

When the killing treatment was discontinued before elapse of a substantial portion of the time required for final death of all mussels in the test tray, the following results were observed under New England conditions:

1 A few mussels had already reached final death.

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[21] The Control of Fouling Organisms in Fresh- and Salt-Water Circuits, by J. G. Dobson, Trans. ASME, vol. 68, 1946, pp. 247–265.

2 Some mussels which survived the treatment period died subsequently, even in sea water at atmospheric temperatures.

3 Other mussels which survived the treatment did not die subsequently when returned to sea water at atmospheric temperatures but instead recovered to various degrees.

Item 1 is as expected from the principle of progressive killing described in the paper. Item 2 is illustrated by data by Dr. Fox in the paper published on pages 127–132 of this issue. With respect to item 3, various degrees of recovery were evidenced by: voluntary closing of shells after water was poured from the test tray, voluntary opening of shells when water was replaced, voluntary extension of the mantle from between the shells and retraction, extension and retraction of the foot, movement of the mussel along the floor of the tray, climbing of side wall of tray, secretion and attachment of new byssus threads.

Recovery was very gradual, in some cases occupying weeks. Under such circumstances positive determination of the final condition of the specimens would have consumed much more time and attendance than was available. Therefore, to meet urgent engineering requirements, all treatments of the tests presented in the paper were continued until final death of all mussels in the test tray, to assure positive killing. The numerical values are specific only for the location, times, and treatment stated. Local tests are recommended for each individual site.

Several sources of uncertainty were observed to arise in a small percentage of cases under the procedure adopted. One possible source of error was the deferred opening of the shells after death had occurred. This delay was detected, in some cases at least, by flotation of the specimen. In cases where the shells were attached close to the bottom of the test pan, flotation was shown by carefully cutting the retaining threads. Delay in the opening of the shells was also indicated at times by the release of minute gas bubbles from between the shells of an individual mussel. Other possible sources of error were observed, but formal discussion would require more specific and detailed observation over a wide range of conditions. Where time of death was uncertain, specimens were eliminated from the tests. Since practical application of the small-scale tests would require observation of a given treatment under actual conditions of commercial operation and subsequent readjustment, the results were considered adequate for the purpose of the exploratory tests if applied with reasonable factors of safety.

While the immediate engineering objectives have been met, it is hoped that others will have opportunity to develop refinements which will lead to more precise control through more detailed observation. Data by Dr. Fox is a valuable contribution in this direction, as illustrating specifically the possible reduction in the duration of a treatment in the upper temperature range by taking advantage of delayed death. It is hoped that others may study the possibility of similar reduction in the lower temperature range, appropriate to chlorination.

It would appear necessary to have available more observational data on the reaction of the organisms under the various conditions of habitat and at various temperature levels before making direct comparison of results obtained at different sites by different procedures.

We concur with Dr. Hutchins that there would be great value in extending the observations of killing treatments at many more sites to show the maximum range of the reaction of the mussels in various geographical locations for different years and seasons. A rather simple test procedure might encourage wider participation by regular operating personnel of industrial plants.

Comparison of results obtained at different sites would be facilitated if test procedures could be standardized as originally proposed. In this Dr. Fox concurs. For the present, possibly two types of procedures might be set up:

1 A test, for adoption where opportunities permit, for more precise observation at a given site by a suitably equipped biologist.

2 A simpler procedure which might find wider use by personnel of industrial plants.

In any case, it would seem appropriate to examine further the procedure for determination of residual chlorine as proposed by Mr. LaQue.

### CLOSURE TO PAPER (4) BY W. L. CHADWICK, F. S. CLARK, AND D. L. FOX

The authors are grateful for the interesting and valuable comments contributed in the several discussions of their paper.

Mr. Elliot and Mr. Estcourt have asked about selection of pipe diameter for the sea lines. Several factors influenced the choice of diameter, the principal ones being cost and availability. The first units at Redondo Steam Station were constructed under an extremely close time schedule and many items were selected because of early delivery. In the early stages of design, consideration was given to the use of 9-ft-diam pipe, which would have given reasonable maximum velocities and friction losses, even allowing for a considerable accumulation of marine growth and debris. Flow calculations were based on Williams' and Hazen's formula for friction coefficients of 120 initially and of 90 for extreme allowable fouling. However, when contract bids were available and, hence, when construction costs and deliveries could be considered, it was found that one bidder had forms and equipment for handling 10-ft-diam pipe already available, and that the 10-ft-diam pipe was offered with earlier delivery at practically the same installed cost as the 9-ft-diam pipe. Accordingly, the choice was made on this basis.

Mr. Estcourt also inquired as to the effect of temperature control on the portion of the circulating-water system between the screens and the condenser. During the 1949 season, elevated temperatures have been employed throughout the entire salt-water circuit with beneficial results. The fouling has been greatly reduced in the condensers and in the lines between the condensers and the gates. Furthermore, a marked reduction in the amount of slime adhering to the condenser tubes has been noticed during this period. At this time (November, 1949), chlorine has not been used for 16 months, either for mussel or slime control.

Dr. Hutchins and Mr. Martin have questioned the estimated annual cost of chlorination. The estimate may seem high, but it was based on the rate of chlorination which experience in this area has indicated would be necessary to obtain satisfactory control of the severe fouling which would be expected at Redondo.

The authors would like to emphasize that at Redondo Steam Station provision for elevated-temperature control of the fouling did not involve a significant increase in cost. Since along the exposed coast at the plant site an accessible intake structure was not feasible, full provision for reversal of flow was necessary in order to provide for chlorination from the shore, hence only a small additional capital expenditure was required in order to permit raising the temperature of the discharge.

The authors are indebted to Mr. T. M. Hotchkiss for his able assistance in the preparation and presentation of the paper.

Mr. Blair mentions *Mytilus californianus* as the most common fouling mollusk on the Pacific Coast. In this connection it should be pointed out that *Mytilus edulis* likewise occurs on the Pacific Coast in vast numbers, and that it is, in fact, more tolerant toward both heterosmotic and thermal extremes than is *Mytilus californianus*. *Mytilus edulis* constitutes by far the most prominent fouling organism in sea-water conduits on the Southern California coast.

The point raised by Messrs. Elliott, Heinemann, LaQue, and Powell, regarding the relative thermal resistance of fouling organisms as correlated with temperatures prevailing in their natural habitat, is very well made. This is indeed a recognized fact which applies to physiological races of the same species. *Mytilus edulis*, being a widely distributed form, is an outstanding example of thermal adaptability. This matter should always be kept in mind if construction of new sea-water tunnels is to be undertaken at contrasting latitudes.

Concerning the temperature and time thresholds for killing mussels at Lynn, it will be of great interest to learn exactly what kind of observational data were collected for the recognition of death or approaching death. A mussel which has received lethal thermal treatment may not necessarily die on the same day, but may expire a day or two later, even after cool flowing sea-water has been restored.

Failure to spin new byssus threads, persistent gaping of the valves, even after mechanical stimulus, or ''sulking'' (i.e., remaining with valves continuously closed) for long periods, after the return from a warm environment to water of normal temperatures, are recognized signs of moribundity. Needless to say, such signs are of paramount importance if one is to make accurate determinations of the critical temperature and time required for lethality.

# Forming of a Plastic Sheet Between Fixed Cylindrical Guides With Coulomb Friction[1]

BY H. I. ANSOFF,[2] SANTA MONICA, CALIF.

**The purpose of this investigation was to obtain a rigorous analysis of the drawing of a plastic sheet between two fixed cylindrical surfaces. A number of solutions have recently been given (1, 2, 3, 4, 5)[3] in which the following fundamental assumptions are used: (*a*) The material between the cylinders is in a state of plane plastic flow and behaves according to the Saint Venant-Mises theory; (*b*) the normal stress in the direction of drawing $\sigma_x$ and the normal stress at the boundary $\sigma_n$ are the principal stresses, (*c*) the horizontal stress $\sigma_x$ is constant over each cross section. In the present treatment only assumption (*a*) is retained. Shevchenko (4) has recently solved this problem assuming that the shearing stress at the walls is proportional to the relative velocity between the wall and the plastic material.**

## STRESS DISTRIBUTION IN PLANE PLASTIC FLOW

CONSIDER the plane flow of a plastic material in the $x$, $y$-plane and let $\sigma_x$, $\sigma_y$, and $\sigma_z$ be the normal stresses in the $x$, $y$, and $z$-directions, respectively, and $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ the shearing stresses. For plane plastic flow

$$\tau_{xz} = \tau_{yz} = 0 \text{ and } \sigma_z = \frac{1}{2}(\sigma_x + \sigma_y)$$

Thus the state of stress can be described completely in terms of $\sigma_x$, $\sigma_y$, and $\tau_{xy}$; the latter stress component, for convenience, will be denoted by $\tau$.

The dependence of the stress components on the orientation of the co-ordinate axes is easily described by means of Mohr's[4] circle. Consider an arbitrary point $P$ in the stressed medium and let a surface element through $P$ and perpendicular to the $x$, $y$-plane be rotated continuously about the parallel to the $z$-axis through $P$, Fig. 1. Further, let $\alpha$ denote the counterclockwise angle between the element and the negative $y$-axis and $\sigma_\alpha$ and $\tau_\alpha$, the stresses transmitted from the unshaded to the shaded side of the element. Thus, for example, $\sigma_0 = \sigma_x$, $\tau_0 = -\tau$ and $\sigma_{\pi/2} = \sigma_y$, $\tau_{\pi/2} = \tau$ as shown in Fig. 1. Now, for any given position of the surface element, the stresses transmitted across it are represented by the co-ordinates of a point on the circumference of a circle with center $[(\sigma_x + \sigma_y)/2, 0]$ and the radius equal to the maximum shearing stress

$$\tau_{\max} = \sqrt{\frac{1}{4}(\sigma_x - \sigma_y)^2 + \tau^2}$$

Fig. 2 shows this circle and, in particular, the points representing the stresses transmitted across the various surface elements shown in Fig. 1. It should be noted that the angle between any two points on the circumference is twice the angle between the corresponding elements of Fig. 1.

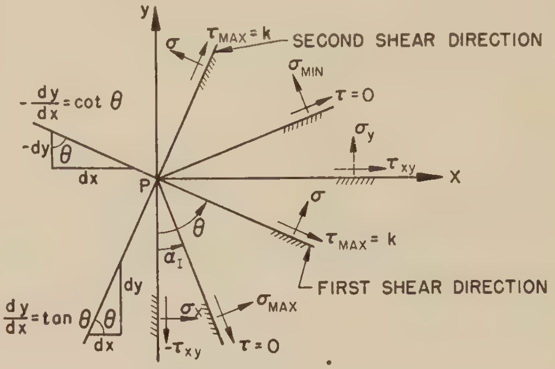

FIG. 1 STRESS DISTRIBUTION IN A PLANE

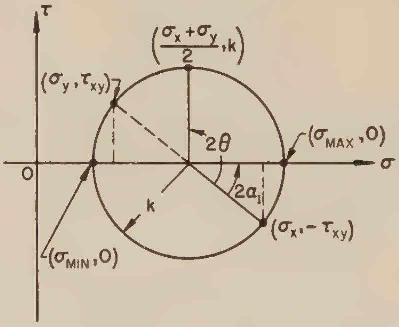

FIG. 2 MOHR'S CIRCLE

The following terminology will be used in the subsequent discussion. At two definite angles $\alpha = \alpha_{I}$ and $\alpha = \alpha_{II} = \alpha_{I} + \pi/2$ the normal stress becomes maximum and minimum, respectively, and the shearing stress vanishes. The directions defined by $\alpha_{I}$ and $\alpha_{II}$, Fig. 1, are called the "first" and "second principal directions," respectively. The shearing stress becomes maximum for the angles $\alpha = \theta_{I} = \alpha_{I} + \pi/4$ and $\alpha = \theta_{II} = \alpha_{II} + \pi/4$. The corresponding directions are called the "first" and "second shear directions," respectively. Thus the first shear direction is along the bisector of the counterclockwise angle between the first and the second principal directions. In the following it will be convenient to omit the subscripts and to designate the angle between the negative $y$-axis and the first shear direction by $\theta$.

The curves in the $x$, $y$-plane which are everywhere tangent to the first shear direction form the "first family of shear lines." The "second family of shear lines" is similarly defined as the

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[2] The Rand Corporation. Jun. ASME.

[3] Numbers in parentheses refer to the Bibliography at the end of the paper.

[4] See, for example, reference (8).

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—SA-22.

family of curves which is everywhere tangent to the second shear direction. Shear lines of different families intersect each other at right angles.

### Basic Equations

The discussion in the preceding section applies generally to the state of stress under conditions of plane strain. If the stressed material is elastic, then the radius of Mohr's circle varies with the position of the point $P$. If, on the other hand, the material is in the plastic state, then, according to the Saint Venant-Mises theory, the maximum shearing stress has a constant value $k$ throughout the plastic region. Accordingly, Mohr's circle has the same radius $k$ for any point $P$ in the plastic region and the stresses in the plastic region are then related by

$$(\sigma_x - \sigma_y)^2 + 4\tau^2 = 4k^2 \qquad [1]$$

If body and inertia forces are neglected, the equilibrium equations take the form

$$\left.\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau}{\partial y} &= 0 \\ \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau}{\partial x} &= 0 \end{aligned}\right\} \qquad [2]$$

Under appropriate boundary conditions, Equations [1] and [2] completely determine the state of stress in the medium without reference to the stress-strain laws. The problem then is statically determinate.

With

$$\omega = (\sigma_x + \sigma_y)/4k \qquad [3]$$

the stresses may be written in the following form, see Fig. 2

$$\left.\begin{aligned} \sigma_x/k &= 2\omega + \sin 2\theta \\ \sigma_y/k &= 2\omega - \sin 2\theta \\ \tau/k &= -\cos 2\,\theta \end{aligned}\right\} \qquad [4]$$

In Equations [4], $\omega$ is one half of the mean normal stress divided by the yield stress in pure shear $k$, and $\theta$ is the angle between the negative $y$-axis and the first shear direction.

Substitution of Equations [4] into [1] yields an identity, and substitution into Equations [2] yields

$$\left.\begin{aligned} \omega_x + \theta_x \cos 2\theta + \theta_y \sin 2\theta &= 0 \\ \omega_y + \theta_x \sin 2\theta - \theta_y \cos 2\theta &= 0 \end{aligned}\right\} \qquad [5]$$

where the subscripts $x$ and $y$ indicate differentiation with respect to these variables.

Let

$$\xi = \omega + \theta, \quad \eta = \omega - \theta \qquad [6]$$

Substitution of Equations [6] into Equations [5], yields the canonic form of the partial differential equations of plane plastic flow (7)

$$\eta_x - \eta_y \cot \theta = 0 \qquad [7a]$$

$$\xi_x + \xi_y \tan \theta = 0 \qquad [7b]$$

From Equations [6], it follows that

$$\theta = \frac{1}{2}(\xi - \eta)$$

Equations [7] are, therefore, quasi-linear.

The characteristic equations of the system, Equations [7], are

$$\frac{dy}{dx} = -\cot \theta \qquad [8a]$$

$$\frac{dy}{dx} = \tan \theta \qquad [8b]$$

The characteristics satisfying Equation [8a] form the "first family of characteristics," and those satisfying Equation [8b] the "second family of characteristics."

Substitution of Equation [8a] into [7a] yields (9)

$$d\eta = \eta_x dx - \eta_y dy = 0 \qquad [9]$$

Hence $\eta$ is constant along each characteristic of the first family. Similarly, substitution of Equation [8b] into [7b] shows that $\xi$ is constant along each characteristic of the second family.

Fig. 1 shows that the equations of the first and the second shear lines are identical to Equations [8a] and [8b], respectively. Hence the first and the second family of characteristics coincide with the first and the second family of shear lines.

### Boundary Conditions

The proposed problem is indicated in Fig. 3. A sheet of material in the plastic state is drawn between two fixed cylindrical surfaces of radius $R$. These surfaces are assumed to be rigid. The thickness of the sheet is $2b$, and the angle which the normal at any point of the boundary makes with the negative $y$-axis is denoted by $\gamma$. Along the surface of the upper cylinder, for instance

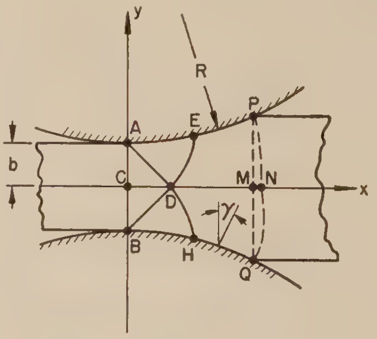

Fig. 3

$$\left.\begin{aligned} x &= R \sin \gamma \\ y &= b + R(1 - \cos \gamma) \end{aligned}\right\} \qquad [10]$$

In the industrial practice the ratio $b/R$ is of the order 1/200. In order to obtain a clearer idea of the stress distribution, however, the ratio $b/R = 1/5$ will be used in the major portion of this paper. (For purposes of comparison with the results obtained by Sachs (1), the problem has also been solved for $b/R = 1/160$. The results are discussed in the next to the last section.)

The following boundary conditions are now prescribed:

(*a*) The exit section $AB$ is assumed free from lateral compression, i.e., it is assumed that $\sigma_y = 0$ along $AB$.

(*b*) A uniform normal stress is assumed to be applied along $AB$.

(*c*) It is assumed that the shearing stress exerted by the walls on the plastic material is directly proportional to the normal pressure and acts in the direction of the relative velocity of the walls with respect to the material. From Fig. 4 it is clear that in our case the normal pressure $p = -\sigma_n$, where $\sigma_n$ is the normal stress at the walls. Since no tension can be transmitted by the walls, $\sigma_n \leqq 0$ at all times. According to the sign convention used in Fig. 1, the direction of the applied shearing stress is positive. Hence $\tau_n = -f\sigma_n$, where $\tau_n$ is the shearing stress along the walls, and $f$ is the constant coefficient of friction.

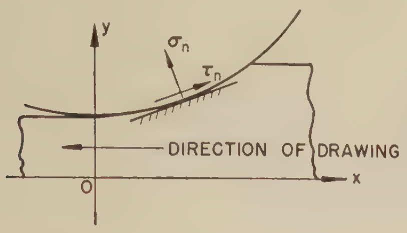

Fig. 4

On the other hand, according to the Saint Venant-Mises theory the shearing stress cannot exceed $k$, the yield stress in pure shear. The friction law at the walls should therefore be modified as follows

$$\left.\begin{aligned}\tau_n &= -f\sigma_n \text{ for } 0 < -f\sigma_n < k\\ \tau_n &= k \qquad \text{for } -f\sigma_n \geqq k\end{aligned}\right\} \ldots\ldots\ldots\ldots [11]$$

From the definitions of $\theta$ and $\gamma$, it follows that the angle between the tangent to the boundary and the first shear direction is $\theta - \gamma + \pi/2$. The corresponding angle along Mohr's circle is $2(\theta - \gamma) + \pi$, and the stresses at the boundary are

$$\left.\begin{aligned}\sigma_n/k &= 2\omega - \sin 2(\theta - \gamma)\\ \tau_n/k &= -\cos 2(\theta - \gamma)\end{aligned}\right\} \ldots\ldots\ldots\ldots [12]$$

Thus simultaneous solutions of Equations [11] and [12] determine the stresses at the boundary.

The state of stress at a boundary point is represented by a Mohr circle with the radius $k$. The location of the center of the circle depends upon the value of $\omega$. Three representative positions of the circle are shown in Fig. 5.

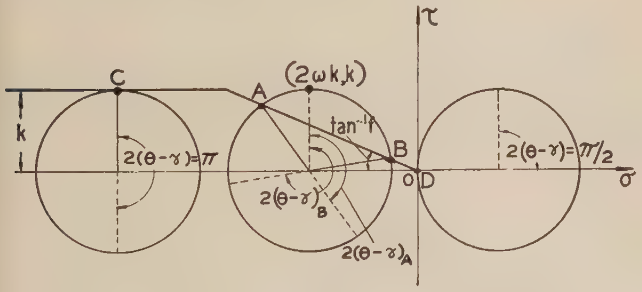

Fig. 5

The graph of $\tau_n$ versus $\sigma_n$ satisfying Equations [11] consists of a straight line parallel to the $\sigma$-axis for $\sigma \leqq -k/f$, and a straight line passing through the origin with a slope equal to $-f$ for $-k/f \leqq \sigma < 0$, as shown in Fig. 5. The points which this graph has in common with the Mohr circle (such as $A$ and $B$, $C$ and $D$) represent the solutions of the system Equations [11] and [12]. As seen from Fig. 5, the angle $\theta - \gamma$ for point $B$ is greater than $\pi/2$. When $\theta - \gamma$ reaches $\pi/2$, the characteristics of the first family become tangent to the boundary and further increase in $\theta - \gamma$ is physically meaningless. Therefore for any given value of $\omega$, the point $A$ represents the only solution which has physical meaning.

Examination of Fig. 5 now yields the following ranges of $\theta - \gamma$;

If $\quad 2\omega \leqq -1/f, \quad$ then $\theta - \gamma = \pi/2 \ldots\ldots\ldots\ldots$ [13a]

If $\quad -1/f < 2\omega \leqq 1, \quad$ then $\pi/2 > \theta - \gamma \geqq \pi/4 \ldots\ldots$ [13b]

Elimination of $\sigma_n$ and $\tau_n$ from the first Equations [11] and [12] yields, with the aid of Equation [6]

$$\gamma - \xi = -\beta - \frac{1}{2}\sin 2\beta - \cos 2\beta \ldots\ldots\ldots\ldots [14]$$

where $\beta = \theta - \gamma$ and the coefficient of friction $f$ has been set equal to 0.5.

The angle $\gamma$ is known at any point on the boundary (see Equations [10]). If $\xi$ is also known, Equation [14] can be solved for $\beta$. The result will fall into one of two possible cases:

($a$) If a real solution does not exist, or if $\beta > \pi/2$, Equation [13$a$] applies. In this case

$$\theta = \frac{\pi}{2} + \gamma \ldots\ldots\ldots\ldots\ldots\ldots [15a]$$

($b$) If the solution is in the range $\pi/2 > \beta > \pi/4$, Equation [13$b$] applies. In this case

$$\theta = \beta + \gamma \ldots\ldots\ldots\ldots\ldots\ldots [15b]$$

With $\theta$ and $\xi$ now known, $\sigma_n$ and $\tau_n$ can be computed directly using Equations [6] and [12].

## Solution in the Region $ABD$

In this paper the term "solution" of Equations [7] shall mean a determination of the families of characteristics defined by Equations [8] and the conditions at the boundary. It has been shown in the section "Basic Equations," that $\xi$ and $\eta$ are constant along characteristics of their respective families. Thus once the characteristic field is determined, the values of both $\xi$ and $\eta$ are known at the point of intersection of any two characteristics. The stresses at this point are then easily computed from these values by means of Equations [6] and [4].

It will be shown in the next three sections of this paper that the solution of Equations [7] can be carried out separately in three well-defined regions in the plastic material. The first region consists of the right triangle $ADB$, Fig. 3, the second region of two curvilinear triangles $ADE$ and $BDH$, and the third region of the rest of the plastic material between the rolls. The solutions in the first two regions are trivial in nature and are called "lost" solutions for reasons to be pointed out in a later section.

According to conditions ($a$) and ($b$) given in the section "Boundary Conditions," $\sigma_x$ = const and $\sigma_y = 0$ along $AB$, Fig. 3. From the yield condition Equation [1], it follows that $\tau$ is also constant along $AB$. Furthermore, at $A$ the shearing stress $\tau = \tau_n = 0$, according to Equations [11], Equation [1] yields

$$\left.\begin{aligned}\sigma_x &= 2k\\ \tau &= 0\\ \sigma_y &= 0\end{aligned}\right\} \text{ along } AB \ldots\ldots\ldots\ldots\ldots [16]$$

This makes $AB$ the first principal direction. Consequently, $\theta$ is constant along $AB$ and is equal to $\pi/4$. Also from Equation [3]

$$\omega = \frac{\sigma_x + \sigma_y}{4k} = \frac{1}{2} \text{ along } AB \ldots\ldots\ldots\ldots [17]$$

Then, by Equations [6], $\xi$ and $\eta$ are constant along $AB$ and, in turn, $\omega$ and $\theta$ are constant throughout the region bounded by $AB$ and two rectilinear characteristics $AD$ and $BD$. Thus $ABD$ is a "region of constant stress." The first family of characteristics, corresponding to the first shear lines, consists of straight lines parallel to $AD$. The value of $\eta$ is constant along the characteristics of this family. The second family is formed by straight lines parallel to $BD$. The value of $\xi$ is constant along the characteristics of this family. From Equations [6] it follows that

$$\left.\begin{aligned}\xi_0 &= \frac{1}{2} + \frac{\pi}{4} = 1.285\\ \eta_0 &= \frac{1}{2} - \frac{\pi}{4} = -0.285\end{aligned}\right\}\text{ in region } ABD\ldots\ldots\ldots[18]$$

Note that Equations [7] are identically satisfied in $ABD$.

### Solution in Region *ADE*

Because of the symmetry of the stress distribution with respect to the $x$-axis, the remainder of the solution will be obtained only for $y \geqq 0$.

The region $ADE$ is bounded by a portion of the boundary $AE$, a characteristic of the first family $AD$, and a characteristic of the second family $DE$. All of the characteristics crossing $AD$ from region $ADB$ have the same value of $\xi_0$. Therefore $\xi$ is constant throughout region $ADE$.

From Equations [6] it follows that $\eta = \xi_0 - 2\theta$. Hence $\theta$ is constant along any characteristic of the first family. The characteristics are straight lines and their equations are found by direct integration of Equation [8$a$]. Thus

$$y = -x \cot\theta + f(\theta)\ldots\ldots\ldots\ldots\ldots\ldots[19]$$

where $f(\theta)$ is to be determined from the boundary values which are given by Equations [10], [14], and [15]. Because of the transcendental nature of these equations, the following procedure is used in determining $f(\theta)$:

A graph of $\gamma - \xi$ is plotted versus $\beta$ for the full range of $\beta$ allowed by Equations [15]. Then for any given value of $x$, the corresponding values $\gamma$ and $y$ are determined from Equations [10] and, using $\xi = \xi_0 = 1.285$, the appropriate value of $\beta$ is read off from the graph. The angle $\theta$ is then determined from Equations [15], and the value of $f(\theta)$ from Equation [19]. The value of $\xi$ is constant throughout the region $ADE$. Equation [7$b$] is satisfied identically, and it remains to determine only the characteristic $DE$ which forms a boundary of the region. Equations [8$a$] and [19] form a system of simultaneous equations

$$\frac{dy}{dx} = \tan\theta, \text{ and } y = -x\cot\theta + f(\theta)\ldots\ldots\ldots[20]$$

where $f(\theta)$ is now assumed known. It is possible to eliminate $x$ from these equations and to obtain an integral for $y$ in a closed form.[5] In the present problem, however, $f(\theta)$ is transcendental and it is simpler to solve the system, Equations [20], by step-by-step integration. The resulting characteristic is shown in Fig. 6 together with a few characteristics of the first family plotted for equal steps in $\gamma$. A characteristic family (such as shown in Fig. 6), consisting of nonintersecting straight lines, is said to form a "noncentered fan."

### Solution in Region *PEDM* by Method of Finite Differences

The following boundary conditions are prescribed in this region.[6] Along the boundary $EP$ Equation [14] must be satisfied. Along the characteristic $DE$ the values of $\xi$ and $\eta$ are given. Along the $x$-axis $\tau$ must be zero for reasons of symmetry and therefore from Equations [4]

$$\theta = \frac{\pi}{4} \quad\text{for}\quad y = 0\ldots\ldots\ldots\ldots\ldots\ldots[21]$$

Since both $\xi$ and $\eta$ vary in this region, Equations [7] and [8] no longer simplify and must be solved by an approximate procedure. Two alternative methods of solution have been used in this problem. The first, discussed in this section, consists of reducing Equations [7] to a system of linear difference equations. The second consists of constructing the characteristic families, Equations [8], by using approximate radii of curvature; it is taken up in the next section.

Equations [7] can be linearized by interchanging dependent and independent variables provided the Jacobian of the transformation,

$$\frac{D(\xi,\ \eta)}{D(x,\ y)} = \xi_x\eta_y - \xi_y\eta_x\ \ldots\ldots\ldots\ldots\ldots[22]$$

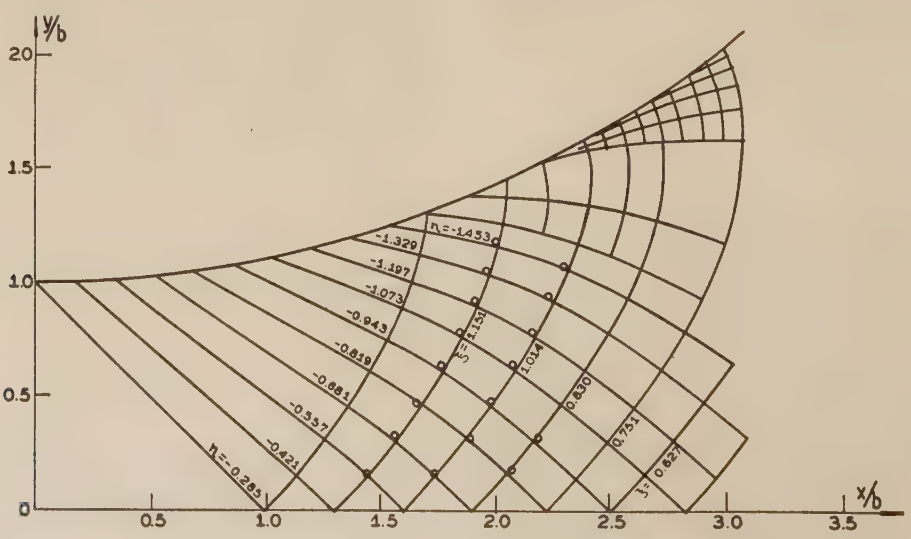

Fig. 6 Graphical Solution Using Approximate Radii of Curvature for $b/R = 1/5$, $f = 0.5$

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[5] Reference (4), p. 5.

[6] This type of problem, in which the boundary is composed in part of a characteristic and in part of a geometric contour with a reflection condition, is known as the "mixed problem" in the theory of partial differential equations.

does not vanish identically in *PEDM*.[7] Since $\xi$ and $\eta$ both vary in *PEDM*, this condition is clearly satisfied. The indicated transformation yields

$$y_\eta - x_\eta \tan\theta = 0, \qquad y_\xi + x_\xi \cot\theta = 0 \ldots\ldots [23]$$

where $\theta = (\xi - \eta)/2$.

To obtain the difference equations, assume that two intersecting characteristics have been determined completely, Fig. 7, and that from two arbitrary points $(k, l - 1)$ and $(k - 1, l)$, it is desired to construct two more characteristics up to their point of intersection at $(k, l)$. If points $(k, l - 1)$ and $(k - 1, l)$ are sufficiently close to $(k - 1, l - 1)$, Equations [23] can be replaced by the approximate expressions[8]

$$\frac{y_{k,l} - y_{k,l-1}}{\Delta\eta} - \frac{x_{k,l} - x_{k,l-1}}{\Delta\eta} \tan\frac{\theta_{k,l} + \theta_{k,l-1}}{2} = 0 \ldots [24a]$$

$$\frac{y_{k,l} - y_{k-1,l}}{\Delta\xi} + \frac{x_{k,l} - x_{k-1,l}}{\Delta\xi} \cot\frac{\theta_{k,l} + \theta_{k-1,l}}{2} = 0 . [24b]$$

These equations are homogeneous in $\Delta\eta$ and $\Delta\xi$, respectively, and represent a system of two linear algebraic equations in three unknowns $x_{k,l}$, $y_{k,l}$, and $\theta_{k,l}$. The determination of these unknowns will differ somewhat depending upon the location of the point $(k, l)$. The following three cases have to be considered:

(*a*) Point $(k, l)$ is on the line $y = 0$, Fig. 8. Then by Equation [21], $y_{k,l} = 0$, $\theta_{k,l} = \pi/4$. Substitution of these values into Equation [24*b*] yields

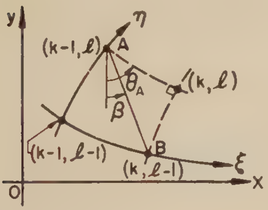

FIG. 7 A CELL OF CHARACTERISTICS

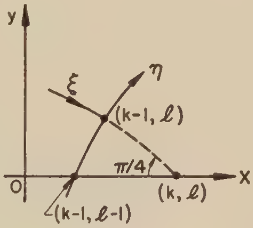

FIG. 8

$$x_{k,l} = x_{k-1,l} + y_{k-1,l} \tan\frac{\pi/4 + \theta_{k-1,l}}{2} = 0 \ldots [25]$$

(*b*) Point $(k, l)$ is inside the region, Fig. 7. From Equations [6]

$$\theta_{k,l} = \frac{\xi_{k,l} - \eta_{k,l}}{2} = \frac{\xi_{k,l-1} - \eta_{k-1,l}}{2} \ldots\ldots\ldots [26]$$

Now let

$$\alpha_{l-1} = \frac{\theta_{k,l} + \theta_{k,l-1}}{2}, \text{ and } \alpha_{k-1} = \frac{\theta_{k,l} + \theta_{k-1,l}}{2}$$

Then Equation [24] yields

$$x_{k,l} = \frac{x_{k-1,l} + x_{k,l-1} \tan\alpha_{k-1} \tan\alpha_{l-1} + (y_{k-1,l} - y_{k,l-1}) \tan\alpha_{k-1}}{1 + \tan\alpha_{k-1} \tan\alpha_{l-1}} \ldots\ldots\ldots [27a]$$

$$y_{k,l} = \frac{y_{k,l-1} + y_{k-1,l} \tan\alpha_{k-1} \tan\alpha_{l-}{}^{1} + (x_{k-1,l} - x_{k,l-1}) \tan\alpha_{l-1}}{1 + \tan\alpha_{l-1} \tan\alpha_{k-1}} \ldots\ldots [27b]$$

(*c*) Point $(k, l)$ is on the boundary, Fig. 9. There are now four unknowns: $x_{k,l}$, $y_{k,l}$, $\theta_{k,l}$ and $\gamma$; and four Equations: [24*a*], two Equations [10], and [14]. Because of the transcendental nature of these equations, they are solved by the following procedure:

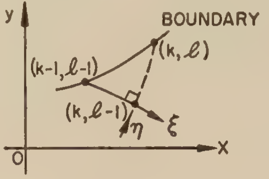

FIG. 9

Starting from an arbitrarily selected point $(k, l - 1)$, an estimate is made of $x_{k,l}$. Then $\gamma$ and $y_{k,l}$ are computed from Equations [10], and $\theta_{k,l}$ is determined from the graph of Equation [14], with the aid of Equations [15]. Equation [24*a*] can be written

$$\tan\frac{\theta_{k,l} + \theta_{k,l-1}}{2} = \frac{y_{k,l} - y_{k,l-1}}{x_{k,l} - x_{k,l-1}} \ldots\ldots\ldots [28]$$

The success of the approximation can now be checked by computing the r.h.s. of Equation [28], and comparing the resulting $\theta_{k,l}$ with the value obtained from the graph of Equation [14]. If the accuracy is insufficient, another estimate of $x_{k,l}$ is made and the entire procedure repeated.

Using the methods of solutions (*a*), (*b*), and (*c*), a network of points can now be plotted starting with the lower left corner of the region *PEDM* and extending as far as desired to the right. If continuous curves are now drawn through corresponding points, the two families of characteristics are obtained, and the solution is completed.

A running check on the accuracy of the computation is afforded by the orthogonal property of the characteristics (see Equations [8]). If at any stage the deviation from the 90-deg angle between two crossing characteristics is undesirably great, the size of the mesh can be decreased until the desired accuracy is reached.

The points computed by this procedure are indicated in Fig. 6 by small circles.

## SOLUTION IN REGION *PEDM* BY USING APPROXIMATE RADII OF CURVATURE

The method used in the preceding section consists essentially of replacing the true curve of a characteristic by a sequence of straight-line segments. W. Prager (7) has recently suggested a method which approximates the characteristic by a sequence of circular arcs.[9] This method improves the accuracy of the approximation and, in addition, represents a considerable saving in the computing time.

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[7] There are three distinct cases in which the Jacobian may vanish: (*a*), $\xi \equiv$ const in the region (*b*), $\eta \equiv$ const. (*c*) $\xi$ and $\eta$ are both identically constant in the region. Cases (*a*) and (*b*) have been treated in the section "Solution in Region *ADE*;" (case *b* occurs in the region *BDH* and becomes identical to case *a* if $\xi$ and $\eta$ are interchanged in the equations). Case (*c*) has been treated in the section, "Solution in Region *ABD*." Since Equations [23] fail to provide solutions for these cases, they are termed "lost" solutions.

[8] This procedure has been used by Sokolovsky (6) and Shevchenko (4).

[9] An alternative graphical method has been given by Prandtl (10). It has been used in parts of this problem where the curvature of the characteristics is small.,

Again consider Fig. 7, and assume that the segment of the $\eta$ = const characteristic from point $(k - 1, l)$ to point $(k, l)$ is a circular arc. The length of the arc $\Delta s$ and the radius $R_\eta$ are related by

$$R_\eta = \frac{\Delta s}{\theta_{k,l} - \theta_{k-1,l}} \qquad [29]$$

The arc length $\Delta s$ is given approximately by

$$\Delta s = \overline{AB} \cos(\theta_A - \beta) \qquad [30]$$

where $\overline{AB}$ is the length of the straight line between $A$ and $B$, and $\beta$ is the angle between $\overline{AB}$ and the negative $y$-axis. Also

$$\theta_{k,l} - \theta_{k-1,l} = \frac{1}{2}[(\xi_{k,l} - \eta_{k,l}) - (\xi_{k-1,l} - \eta_{k-1,l})]$$

$$= \frac{1}{2}(\xi_{k,l-1} - \xi_{k-1,l}) \qquad [31]$$

since

$$\eta_{k,l} = \eta_{k-1,l} \text{ and } \xi_{k,l} = \eta_{k,l-1}$$

Substitution of Equation [30] into [29] yields

$$R_\eta = \frac{2AB\cos(\theta_A - \beta)}{\theta_{k,l} - \theta_{k-1,l}} \qquad [32a]$$

and Equation [31] into [32a]

$$R_\eta = \frac{2A\bar{B}\cos(\theta_A - \beta)}{\xi_{k,l-1} - \xi_{k-1,l}} \qquad [32b]$$

Identical procedure yields for the radius of curvature $R_\xi$ of the $\xi$ = const characteristics

$$R_\xi = -\frac{\Delta s}{\theta_{k,l} - \theta_{k,l-1}} \qquad [33a]$$

and

$$R_\xi = -\frac{2\overline{AB}\sin(\theta_A - \beta)}{\eta_{k-1,l} - \eta_{k,l-1}} \qquad [33b]$$

In Equations [32] and [33] it is assumed that if $\xi$ and $\eta$ form a right-handed system of curvilinear co-ordinates, then positive values of $R_\eta$ and $R_\xi$ mean that the centers of curvature lie in the respective directions of increasing $\eta$ and increasing $\xi$.

As in the previous section, computation will be different for the following cases:

(*a*) Point $(k, l)$ is on the line $y = 0$, Fig. 8. In this case $\theta_{k,l} = \pi/4$, $\beta = 0$ and, because of symmetry with respect to the $y$-axis, $\overline{AB} = 2y_{k-1,l}$. The radius $R_\eta$ is determined from Equation [32*a*].

(*b*) Point $(k, l)$ falls inside the region. Equation [32*b*] and [33*b*] can be used directly.

(*c*) Point $(k, l)$ falls on the boundary. Equation [33*a*] is used in conjunction with Equations [10] and [14]. A guess is made for the value of $R_\xi$ and the corresponding arc is drawn to the boundary. Then $\Delta s$ is measured, the co-ordinates $(x_k, y_k)$ are read off, and $\theta_{k,l}$ is computed from Equations [10] and [14] as in the preceding section. Using Equation [33*a*], radius $R_\xi$ is recomputed and the entire procedure is then repeated until satisfactory accuracy is obtained.

The field of characteristics for the region *PEDM* shown in Fig. 6 has been constructed by this method. At $x/b = 2.32$ the characteristics of the first family become tangent to the boundary, since $\beta$ in Equations [15] reaches the value of $\pi/2$ and hence $\theta - \gamma = \pi/2$. For $x/b > 2.32$ the boundary becomes an "envelope of characteristics."

## RESULTS

Once the characteristic field has been mapped, the stresses at any point of the field are easily determined by the use of Equations [6] and [4], and the stresses at any point of the boundary by Equations [6] and [12].

Fig. 10 shows the stress distribution along the line $y = 0$, and Fig. 11 the distribution plotted versus the distance along the boundary. Figs. 12, 13, and 14 show the stress distribution computed along vertical cross sections taken at different points in the plastic material. The graphs show good qualitative agreement with the results obtained for the frictionless case by Sokolovsky (6) and Shevchenko (4).

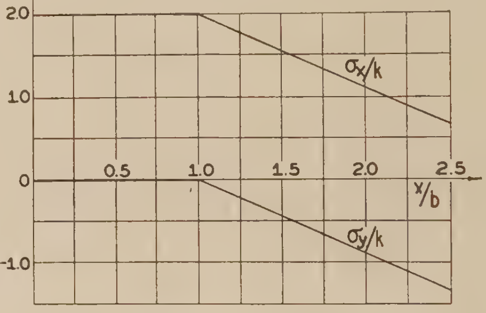

FIG. 10 STRESS DISTRIBUTION ALONG $x$-AXIS

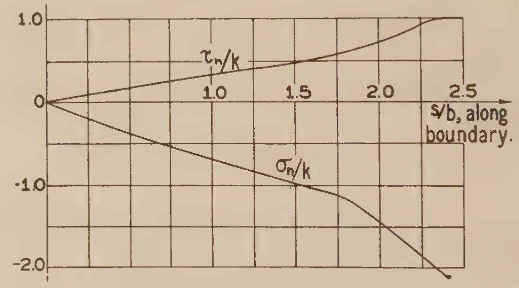

FIG. 11 STRESS DISTRIBUTION ALONG BOUNDARY

It was found that at the beginning of the region *PEDM*, the characteristics can be approximated closely by a single circular arc. This suggests that for small thickness-to-radius ratios the problem can be solved with sufficient accuracy by using a single circular arc to replace the entire segment of a characteristic extending from the center line to the boundary. In addition, if the total angle of grip $\gamma_{\max}$ does not exceed 10 deg, the transcendental friction law at the boundary given by Equation [14] can be linearized, thus simplifying case (*c*) of the preceding section.

With these simplifications the problem has been solved graphically using $b/R = 1/160$ and boundary values of the section, "Boundary Conditions." The resulting stress distribution is shown in Fig. 15. At $x/b = 12$, the horizontal stress along the $y$-axis is $\sigma_x/k = 0.20$, and the normal stress at the boundary is $\sigma_n/k = -1.8$. Sachs (1) gives $\sigma_x/k = 0$, and $\sigma_n/k = -2$ for $x/b = 12$.

## DETERMINATION OF PLASTIC-ELASTIC BOUNDARIES

The process of forming a sheet between fixed guiding surfaces will be one of the following three cases:

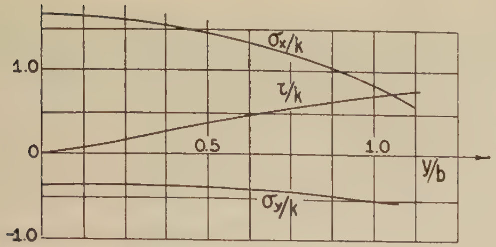

FIG. 12 STRESS DISTRIBUTION ALONG VERTICAL SECTION AT $x/b$ = 1.38

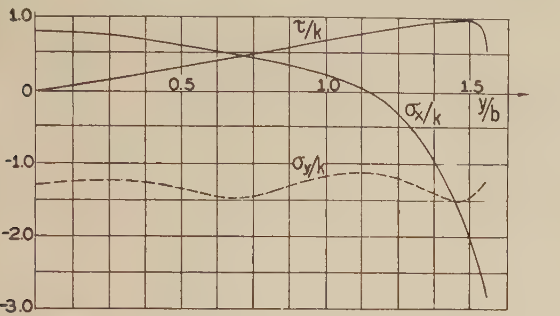

FIG. 13 STRESS DISTRIBUTION ALONG VERTICAL SECTION $x/b$ = 2.32

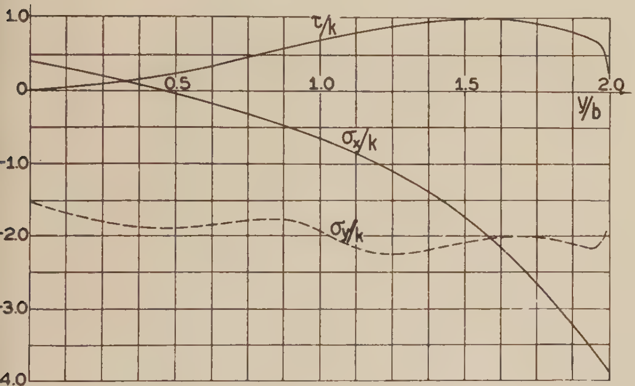

FIG. 14 STRESS DISTRIBUTION ALONG VERTICAL SECTION $x/b$ = 3.0

(*a*) *Pure Drawing.* In this case a drawing force is applied to the sheet at the exit from the guides, but no force is applied at the entrance.

(*b*) *Drawing Under Tension.* A drawing force is applied at the exit and a smaller tensile force at the entrance.

(*c*) *Extrusion.* In this case a compressive force is applied at the entrance and no force at the exit. For the purpose of determining the boundaries between the plastic and the elastic portions of the sheet the three cases may be summarized by requiring that a prescribed resultant horizontal force, say, $F_{AB}$, be applied to the plastic region at the exit from the guides and another horizontal force, say $F_{PQ}$, be applied to the plastic region at the entrance.

A material behaving according to the Saint Venant-Mises theory remains rigid up to the yield point. As a result of this, the entire section of the sheet between the guides must be in a plastic state. Consequently the plastic-elastic boundaries must pass through the points of the boundary (such as $P$, $Q$ and $A$, $B$ in Fig. 3), at which the sheet enters and leaves the guides.

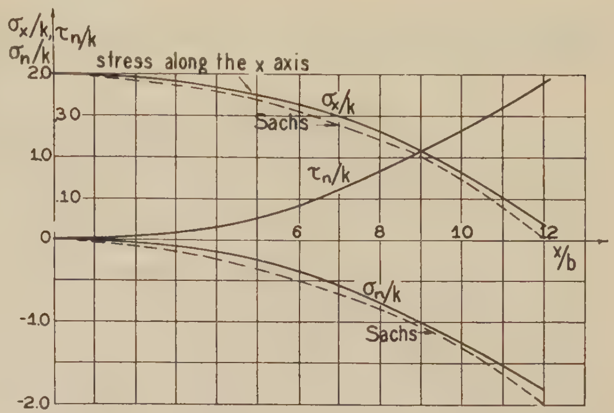

FIG. 15(*a*) STRESS DISTRIBUTION FOR $b/R$ = 1/160, $f$ = 0.224

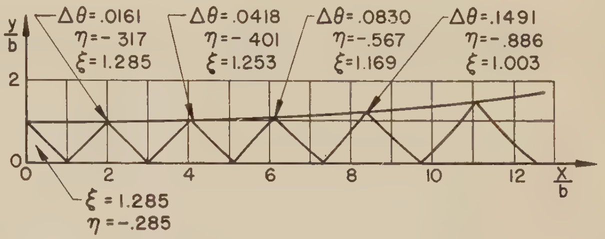

FIG. 15(*b*) GRAPHICAL SOLUTION FOR $b/R$ = 1/160, $f$ = 0.224

On the other hand, the resultant horizontal force transmitted across the boundary from the plastic to the elastic regions of the sheet[10] must be equal to $F_{AB}$ and $F_{PQ}$ at the two respective boundaries. This condition is satisfied automatically at the exit by the method of solution used in this problem. It may be satisfied at the entrance to the guides by the following procedure:

Horizontal stress distributions, such as in Fig. 12, are plotted for a number of vertical sections in the plastic material. By interpolating between adjacent sections, a section is located along which

$$2\int \sigma_x dy = F_{PQ}$$

integration being carried out from the center line to the boundary. If $P$ and $Q$ are used to denote the points at which this section intersects the boundary, then for any curve $C$ joining $P$ and $Q$ through the plastic material

$$\int \sigma_x ds = F_{PQ}$$

the left side representing a line integral along $C$. This relation is easily seen by considering the horizontal equilibrium of a region such as $PMQN$ in Fig. 3. If the initial thickness of the sheet is now made equal to $PQ$, any such curve $C$ will satisfy the conditions imposed on the plastic-elastic boundaries.[11] Thus the thickness of the sheet which may be formed under the conditions of this problem is uniquely determined for any prescribed system of loading.[12]

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[10] The transmitted shearing force will automatically be zero by the symmetry of the shearing stress distribution with respect to the $x$-axis.

[11] Determination of the actual shape of the plastic-elastic boundary curve depends on kinematic as well as dynamic considerations and is too involved to be attempted here.

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[12] It is important to keep in mind that this problem is solved under the assumption of negligible inertia forces. Thus the thickness determined in the foregoing represents the maximum thickness of the sheet which can be formed by the prescribed forces. If the thickness is smaller than the maximum, the sheet will accelerate, and the present solution is no longer applicable. If the thickness is greater, the sheet cannot be formed by the prescribed forces.

[13] A translation of the paper has been prepared for the D. W. Taylor Model Basin, U. S. Navy, by the Graduate Division of Applied Mathematics, Brown University.

# Motor-Generator Locomotives, Their Design and Operating Characteristics

By J. C. FOX,[1] J. F. N. GAYNOR,[2] and F. D. GOWANS[3]

**The motor-generator type of locomotive permits the application of the direct-current series-wound traction motor, with its highly desirable characteristics, to electrifications deriving their power from a single-phase alternating-current trolley. This is of particular benefit in the operation of heavy-drag freight trains on mountain grades. Nearly 30 years of design and operating experience have gone into the development of this type of locomotive. The latest examples are the units recently placed in service on the electrified sections of the Great Northern and Virginian Railways. Noteworthy features in the design, construction, and operation of these units are discussed.**

## General Characteristics

In heavy-drag freight-train service, encountered in mountainous territory, involving relatively long and heavy gradients, the direct-current series-wound motor has much to recommend its use. In addition to relative simplicity of construction, the series-wound motor has the characteristic ability of producing, without appreciable damage to itself, high initial torques without accompanying armature rotation—a characteristic which finds practical utilization when the motor is used in a locomotive that is required to "lay up" against a heavy train in the effort of getting the train under way.

The drop in speed and rapid increase in torque of the series motor as its loading is increased, with the accompanying tendency to maintain, to a certain extent, a relatively constant load on the power source, make this type of motor well suited for traction purposes.

On the other hand, the presence of a commutator on the motor armature restricts the voltage which can be used across the motor to a relatively low value, as transmission and distribution voltages are judged. Hence the desire to employ a high voltage on the contact system is accompanied by the necessity of using a transforming medium between the contact line and the traction motors if these be of the direct-current series-wound type. To date the highest practicable contact-line voltage for direct application to the direct-current series-wound motor is something less than 4000 volts, with the application made by connecting two motor armatures permanently in series and gearing them to a common gear on the driving axle. Thus with something less than 2000 volts per motor armature, valuable space is required for conductor insulation, and this space might better be used for active material, i.e., copper and iron, to secure the maximum output from the restricted spaces in which traction motors are required to work. This is done by the use of relatively low-voltage motors, such as are used in the motor-generator and Diesel-electric types of locomotives.

There is no practically usable static transformer-rectifier combination commercially available to the locomotive builder that will transform high-voltage alternating-current single-phase energy to low-voltage direct-current energy suitable for use with the simple direct-current series-wound motor in traction service. The mercury-arc rectifier, in recent years, has been viewed as a possible candidate for this role. Corrective measures must be taken to minimize primary-power-supply wave distortion, characteristic of single-phase-rectifier operation. Interference must be reduced to values acceptable from the viewpoint of communications-lines interference, which would render this type of transformation unacceptable from the locomotive builder's and operator's point of view.

The alternating-current synchronous-motor direct-current generator set, in combination with a suitable static transformer of the conventional alternating-current type seems to be the most practicable means of energy conversion for locomotive use where direct-current series-wound traction motors are employed.

Hence the motor-generator type of locomotive and its justification in heavy traction service.

## Advantages

There are several incidental but valuable advantages attendant upon the use of the synchronous-motor-generator locomotive. These may be cited as follows:

1 The maintenance of power factor in the railroad-owned transmission and distribution lines at values close to unity, and, in some cases, of leading power factors, is practicable by the control of the synchronous-motor excitation.

2 The motor-generator locomotive is essentially a constant-horsepower machine and, accordingly, the avoidance of large power demands under heavy grade or accelerating conditions is of direct benefit to the operating company's power bills, as influenced by peak-demand charges.

3 The motor generator set and its control lend themselves to flexibility of control functioning during regenerative-braking and motoring periods, with a consequent flexibility of locomotive and train control.

4 The performance characteristics of the locomotive are independent of contact-system voltage drop, down to a limit dictated by synchronous-motor pull-out torque.

5 The performance characteristics of this type of locomotive appear to be admirably suited to the operation of railroads traversing long stretches of terrain at river grade, interrupted with severe mountain gradients of appreciable length. Thus relatively fast schedules are secured for a limited given power demand.

6 Because the motor-generator locomotive is, to a large extent, similar to the Diesel-electric in that both employ driven direct-current generators and associated traction motors, the same design of traction motor can be used in both types of locomotives. Thus the benefits of standardized production of

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Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—SA-7 traction motors are available to the operator of motor-generator locomotives.

## HISTORY

The motor-generator locomotive is not a recent development. The first one built in the United States was an induction-motor-generator unit operating under a 2300-volt 60-cycle single-phase overhead-contact system. This was in the nature of an experimental locomotive built by General Electric in 1910, for a small privately owned railroad desiring to use the commercial form of energy available to it without conversion apparatus. The line has long since been abandoned.

In the middle 1920's the New Haven Railroad purchased five 1120-hp, 1—B+B—1, 138-ton motor-generator freight locomotives, Fig. 1, and two B+B, 100-ton switching locomotives of the same rating (1).[4] These were built for use in electrified territory where contact-system power-factor correction was an objective.

When the Great Northern Railway relocated its line through the Cascade Mountains in the late 1920's, a relocation which involved the abandonment of operation through the old 2.75-mile Cascade Tunnel and the driving of a new bore 7.79 miles in length, 15 years of operating experience with the then existing 6600-volt three-phase electrification indicated that a more flexible system was desirable for the new section of line. Accordingly, the 11,000-volt 25-cycle single-phase system, with motor-generator locomotives, was adopted (2, 3).

The first locomotives purchased for the new electrification were built by Baldwin-Westinghouse as 1—D—1, 179-ton, 1830-hp (cont.) 2165-hp (one-hour) units, operable in multiple in combinations of two to five cabs, see Fig. 2, under the control of one engineman (4). These were supplemented by a 1—C+C—1, 270-ton, 3000-hp (cont.) 3300-hp (one-hour) design built by American Locomotive and General Electric, shown in Fig. 3, also capable of being operated in multiple to provide large concentrations of motive power under the control of a single engineman (5).

## NEW LOCOMOTIVES

Early in 1947 the Great Northern took delivery from the General Electric Company of two B—D+D—B, 360-ton, 5000-hp single-cab locomotives, Fig. 4, bringing the total number of units now operated by this railway to twenty (6).

Table 1 gives dimensional and other salient characteristics of the locomotives composing the Great Northern fleet.

With the delivery in the early part of 1948, of four 6800-hp double-cab 500-ton locomotives (7), the Virginian Railway became the fourth[5] railway in the United States to operate this type of motive power. These locomotives, with somewhat more than a million pounds on drivers, classify as the heaviest (in so far as driver weight is concerned) and the most powerful continuously rated electric locomotives in service in the United States.

Principal characteristics of the Virginian locomotives are shown in Table 2, and one of the units is shown in Fig. 5, at the

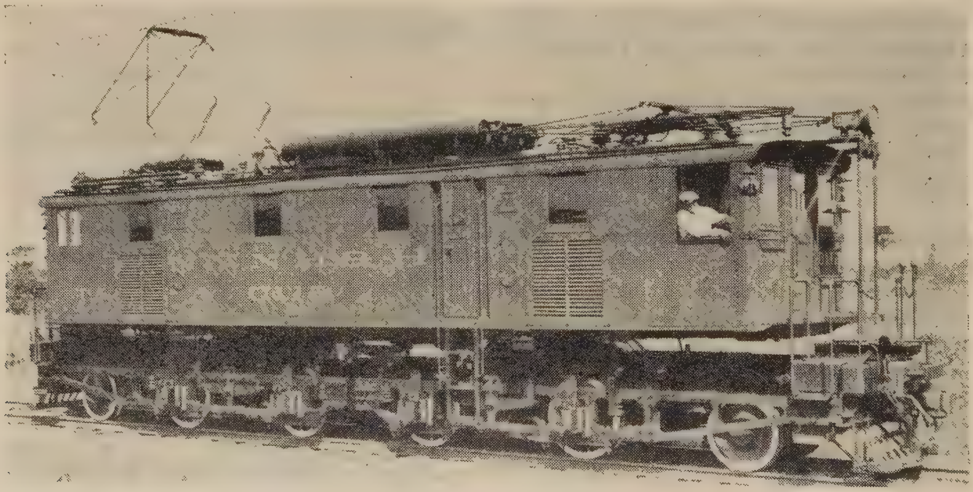

FIG. 1 FREIGHT LOCOMOTIVE ON THE NEW HAVEN RAILROAD

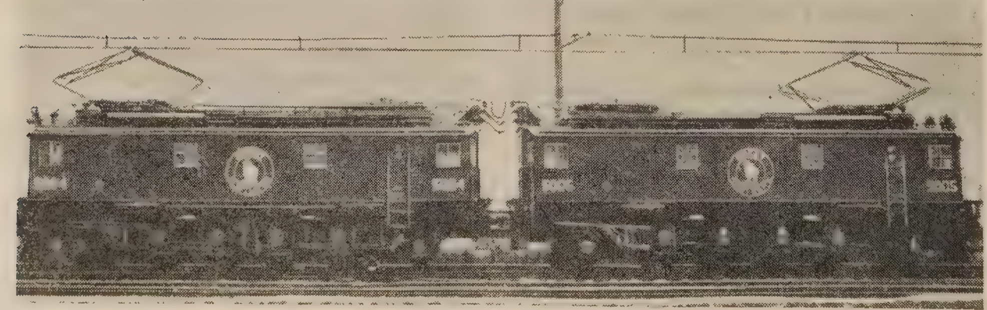

FIG. 2 TWO 1830-HP UNITS BUILT BY BALDWIN-WESTINGHOUSE FOR THE GREAT NORTHERN RAILWAY

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[4] Numbers in parentheses refer to the Bibliography at the end of the paper.

[5] The Detroit, Toledo and Ironton R.R. operated two motor-generator locomotives on a 16.6 route-mile electrification in 1926. This electrification has since been abandoned.

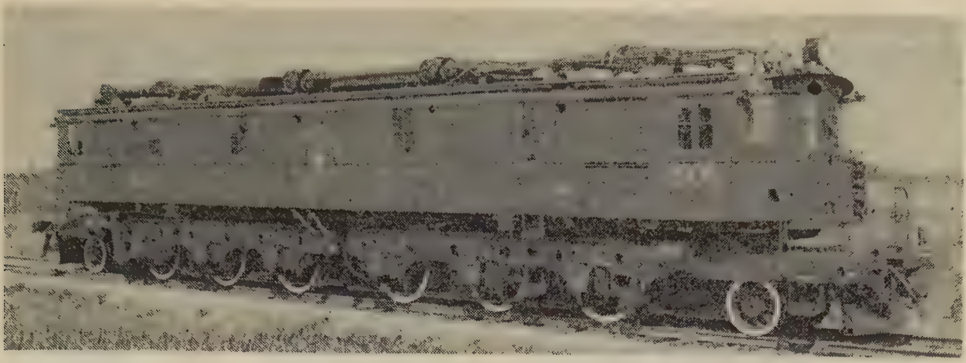

Fig. 3 General Electric 3000-Hp Locomotive for The Great Northern Railway

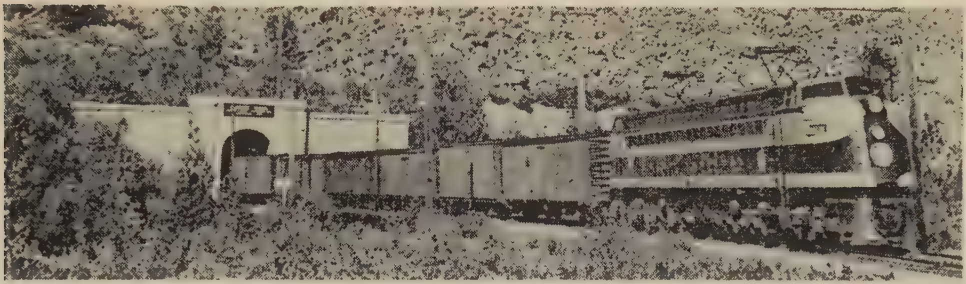

Fig. 4 5000-Hp Freight-Passenger Unit With Train on The Great Northern Railway

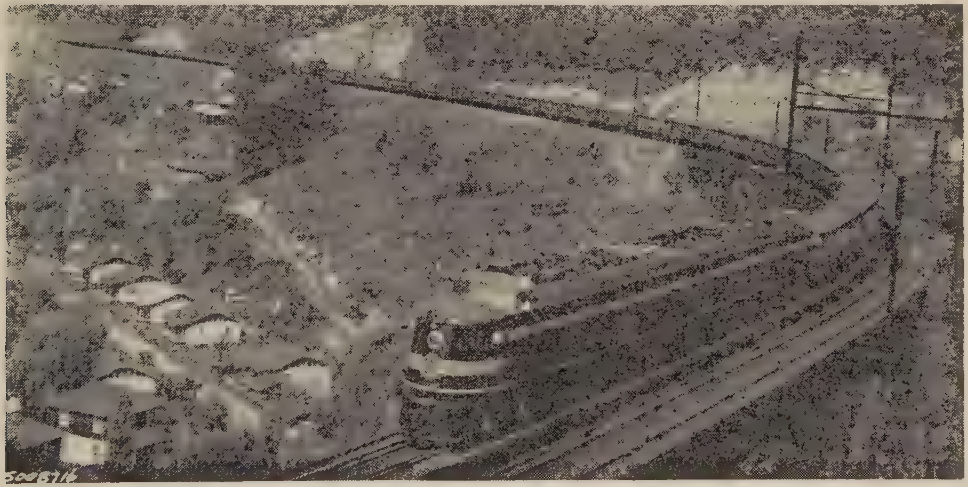

Fig. 5 6800-Hp Double-Cab Locomotive With Train Helped by an Induction-Motored Three-Cab Unit on the Virginian Railway

TABLE 1 GREAT NORTHERN 11,000-VOLT, MOTOR-GENERATOR LOCOMOTIVES

| Builder, mechanical | Baldwin | American | General Elec. |
|---|---|---|---|
| Builder, electrical | Westinghouse | General Elec. | General Elec. |
| Wheel arrangement | 1—D—1 | 1—C+C—1 | B—D+D—B |
| Hp (cont.) at rail | 1830 | 3000 | 5000 |
| Total weight, lb | 371100[a] | 539000[b] | 735000 |
| Weight on drivers, lb | 284800[a] | 426200[b] | 735000 |
| No. driving axles | 4 | 6 | 12 |
| Cont. tract. effort, lb | 44250 | 60500 | 119000 |
| Cont. adhesion, per cent | 15.5 | 14.2 | 16.2 |
| Speed at cont. t.e., mph | 15.5 | 18.6 | 15.75 |
| Max safe speed, mph | 45 | 50 | 65 |
| Length over couplers, ft-in | 47-2 | 73-9 | 101-0 |
| Rigid wheel base, max, ft-in | 16-9 | 15-4 | 16-9 |
| Height over-all, ft-in | ... | 15-3 | 16-0 |
| Driving-wheel diam, in | 56 | 55 | 42 |
| No. in operation | 10 | 8 | 2 |
| Year built | 1926-28-29 | 1927-28-30 | 1947 |

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[a] The first four locomotives weighed 357,700 lb with 275,000 lb on drivers.
[b] The first two units weighed 518,200 lb with 410,600 lb on drivers.

TABLE 2 VIRGINIAN RAILWAY MOTOR-GENERATOR LOCOMOTIVE

| | |
|---|---|
| Builder, mechanical | General Electric |
| Builder, electrical | General Electric |
| Wheel arrangement | 2 (B—B+B—B) |
| Hp (cont.) at rail | 6800 |
| Total weight, lb | 1033832 |
| Weight on drivers, lb | 1033832 |
| No. of driving axles | 16 |
| Cont. tract. effort, lb | 162,000 |
| Cont. adhesion, per cent | 15.8 |
| Speed at cont. tract. effort, mph | 15.75 |
| Maximum safe speed, mph | 50 |
| Length over couplers ft-in | 150-8 |
| Rigid wheel base, maximum, ft-in | 9-0 |
| Height over-all, ft-in | 16-3 |
| Driving wheel diam, in | 42 |
| No. in operation | 4 |
| Year built | 1948 |

head of a 6000-ton train of loaded coal cars, on a 2 per cent grade, with an induction-motored locomotive as a helper at the rear.

It is the purpose of this paper to discuss design features of and operating results secured with the latest Great Northern and the Virginian locomotives. Each of the designs is unique in that the former is the longest single-cab electric locomotive ever constructed, while the latter is the first design of electric locomotive to carry a million pounds on drivers. The design of both locomotives involved problems not heretofore encountered in locomotive-development work.

### Basic Design Considerations

Basic requirements in the case of the Great Northern locomotive were as follows:

1 A total of 5000 hp at the rail at a continuous rating, to be available continuously at a low speed of between 15 and 20 mph.

2 Locomotive to be built in a single-cab unit.

3 All weight to be on drivers.

The specification of 5000 hp at the rail indicated a synchronous-motor rating of 6000 hp, with an over-all electrical-transmission efficiency, between the synchronous motor and rail, of approximately 83.5 per cent. Synchronous-motor design factors, restricted by a permissible stator diameter of 83 in., which allowed a 17 in. width of aisle and 3 in. for each cab-wall thickness, and a synchronous speed of 750 rpm, made necessary the use of two separate set driving motors, each having a continuous rating of 3000 hp.

Similar restrictions, applying to traction-generator design, resulted in the use of two generators to be driven by each of the synchronous motors.

The traction motor which was selected is the GE-746, a standard series-wound motor originally designed for Diesel-electric locomotive applications with maximum axle loading of 60,000 to 62,500 lb on 42-in-diam wheels with 65 mph (top speed) single-reduction gearing. The motor is rated as being suitable for use with a traction generator involving 500-hp input from the prime mover (in this case, the synchronous motor) per traction motor. Thus for a synchronous-motor rating of 6000 hp, twelve traction motors, with a total locomotive weight of 720,000 to 750,000 lb, were indicated.

With these design elements fixed, the over-all problem resolved itself into one of designing a running gear with twelve motored axles that would negotiate 10 deg main-line curvature coupled to trains and 17 deg wye trackage alone, and that would match with a double-end cab of sufficient length to house the two 3000-hp three-unit motor generator sets and their associated auxiliary and control equipment.

Preliminary specifications for the Virginian motive power stipulated a continuous rating such as to permit the haulage of trains as large as those being handled by the three-cab 6000-hp induction-motored locomotives with which the railway has been operating since the electrification of the Mullens-Roanoke section of its line.

The impracticability of mounting so large a rating in a single cab was obvious at the outset and a two-cab locomotive was selected as the basis of design.

A study of the service requirements and the performance of the existing motive power indicated that a locomotive carrying approximately a million pounds on drivers would be required. Since the top speed involved (50 mph) was moderate, it was decided that all weight would be on drivers and no special guiding axles would be required.

The desire to utilize the GE-746 traction motor, with a permissible axle loading of 62,500 lb with maximum reduction gearing resulted in the selection of sixteen motored axles, eight of which were to be located under each of the two cabs. The use of sixteen traction motors, each rated for 500-hp input to the traction generators, fixed the total continuous synchronous-motor capacity at 8000 hp, or two 4000-hp sets. Transmission efficiencies permitted a rail-horsepower rating of 6800 at the speed at which maximum continuous tractive effort of the traction motors occurs.

The selection of an eight-axle running gear for each of the two cabs was narrowed down to two designs, a B—D—B arrangement employing a main frame, integral with the cab structure, and two two-axle swivel trucks; or a B—B+B—B arrangement, employing four identical two-axle swivel trucks.

The second arrangement was selected in the interests of easy maintenance, interchangeability of trucks, and over-all superior flexibility of operation. The resulting locomotive nomenclature of this arrangement of running gear is 2 (B—B+B—B), and each of the two units composing the locomotive is, for all practical purposes, a duplicate of the other. One unit, however, carries two pantographs (one being a spare collector), while the second carries but one. A second collector may be added to the second unit if operating experience indicates this to be advisable.

### Cab Design

In conformity with current appearance styling practices, the cabs of both locomotives have been streamlined, combining appearance with practical utilization of space and good visibility. Nose compartments and operating cabs are practically identical in both designs. A full-size model of these portions of the cabs was made before construction to determine characteristics.

For optimum visibility with a long hood or "nose" section, a 16-ft radius over the cab roof from the track center line at a rail level was used, which results in positioning of the operator's eyes but a few inches below the maximum at the cab center line. The right-hand running rail can be seen from normal eye level at a distance 50 ft ahead of the coupler.

The top of the hood extending down to the level of the window sill is made up on a three-piece form, two outside sections—left and right—and a center section. By changing the width of the center section the form is made suitable for cabs of different widths, within certain limits of course. From the window sill to the bottom of the cab the hood sheets are perfectly straight, cut on a bias, and wrapped around the hood. Above the sills the windows and cab side sheets have been drawn in at an angle of 15 deg. This was done for appearance reasons only in this case, to set off the superstructure from the side sheets and relieve the otherwise boxy appearance. However, in a number of other instances this has been done to meet clearance restriction and is quite practical. On both locomotives the striping and lettering have been arranged to relieve the side-sheet expanse and embrace the air-inlet grilles.

### Platform Design

Although the outward appearances of these locomotive cabs, as shown in Figs. 6 and 7, are very similar, the supporting structures are quite different. This is due chiefly to the horsepower requirements for a single-cab unit. A unit of the Virginian locomotive rating 4000 hp represents the practical maximum rating of a single motor generator which can be accommodated in the width and height available, even though both locomotives are unusually high and wide. The Great Northern locomotive, requiring 6000 hp in a single unit, would not accommodate a set this large, and the cab had to be stretched out to accommodate two 3000-hp sets end to end, as shown in Fig. 8. For this reason the cab is long, with a center-plate distance of 56 ft 6 in. This determined the nature of the structure, which is a truss designed to keep the deflection within design limits.

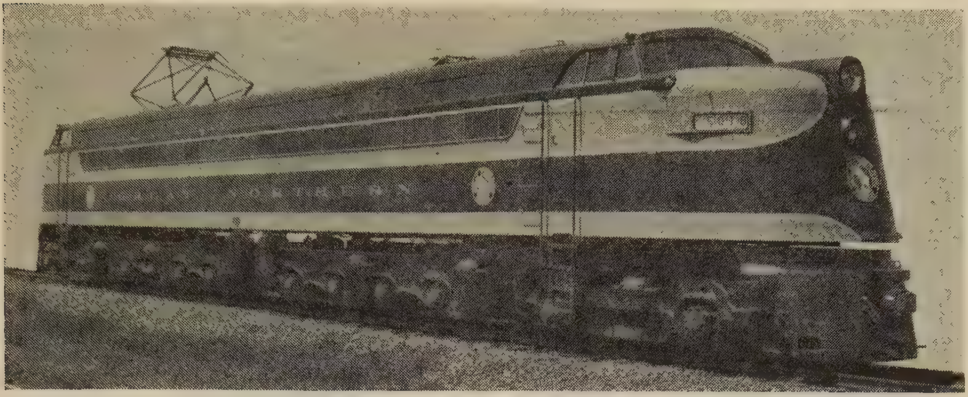


Fig. 6 Great Northern 5000-Hp. Motor-Generator Locomotive

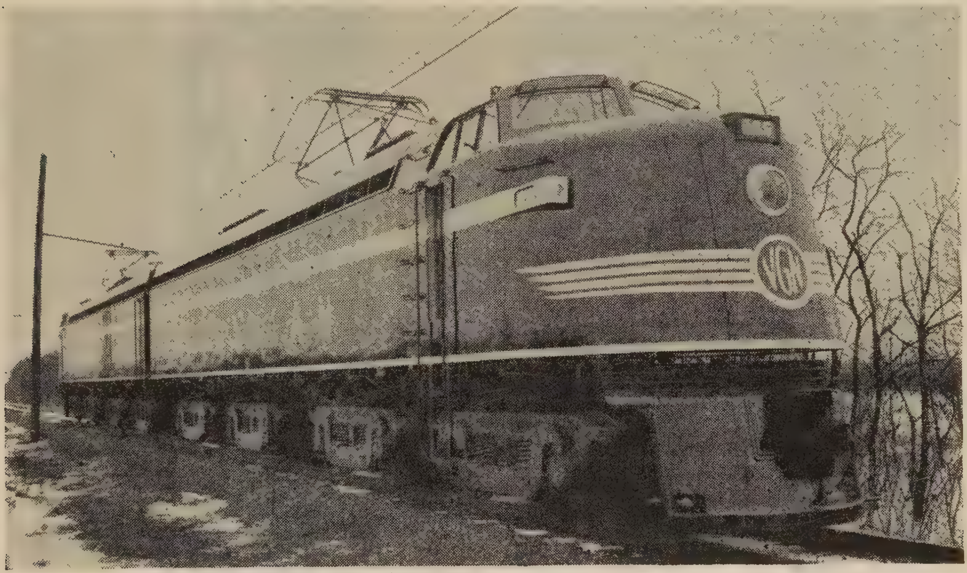


Fig. 7 Virginian 6800-Hp Motor-Generator-Locomotive

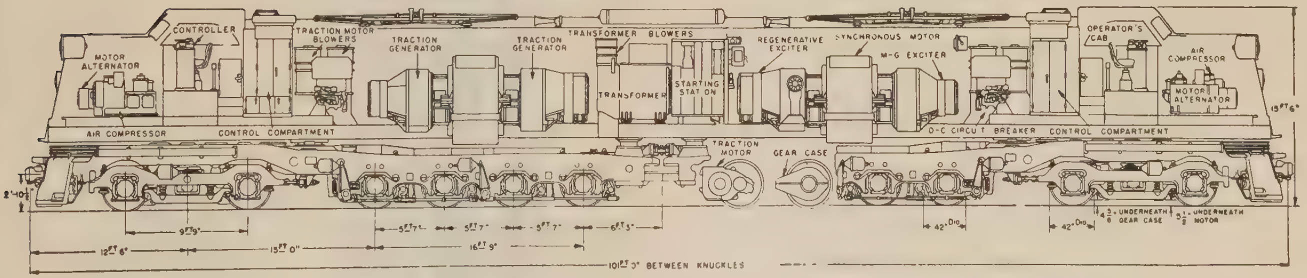


Fig. 8 Cross-Sectional Elevation of 5000-Hp Great Northern Locomotive

The truss supports a central equipment platform with end bulkheads, intermediate cross-ties, and lateral bracing. Fig. 9 shows center of gravity and weight distribution. The symmetry of cab and truss construction, together with equipment location from each end to the center, results in unusually good weight distribution.

On the Virginian locomotive, Fig. 10, the center-plate distance is shorter, namely, 34 ft 6 in., permitting the use of a suitably deep platform instead of a truss. The main sills are 24 in. deep between the bolsters and reduce to 18 in. for the end extensions.

Procurement of the desired weight distribution on the Virginian locomotive was difficult because the large pieces of equipment (motor generator set and transformer) necessarily were forced to the rear by the single-end operating cab and hood. Since the railway desired to avoid the use of loading pads between the cab and truck, all the cab weight had to be carried on the two center plates. By very careful arrangement of equipment, proper weight distribution was secured. The preliminary loading diagram, Fig. 11, shows the center of gravity of the cab only 1 in. to the rear of the center line, and the rear center-plate load only 1730 lb heavier than the front one. The matter of span bolster weight distribution had to be considered since the front

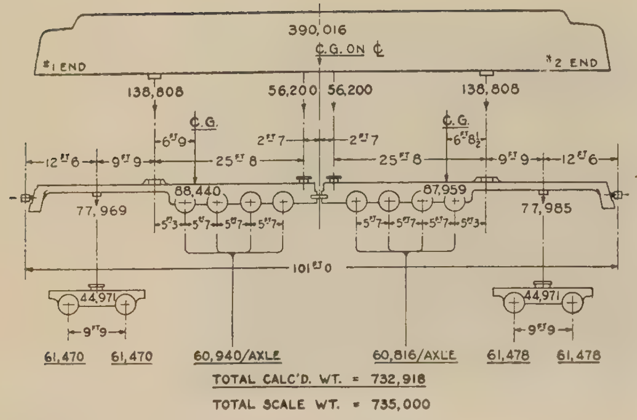


Fig. 9 Weight-Distribution Diagram for Great Northern Unit

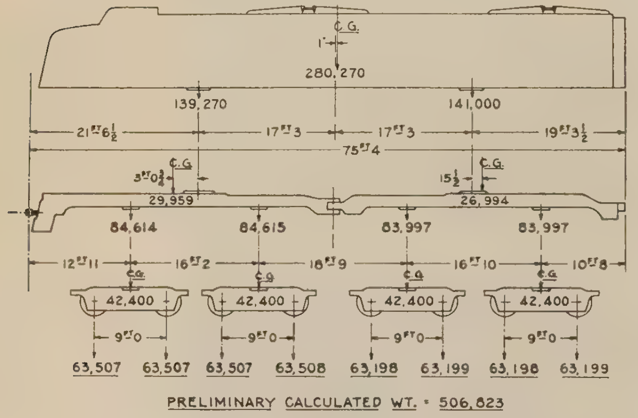


Fig. 11 Preliminary Weight-Distribution Diagram for the Virginian Locomotive

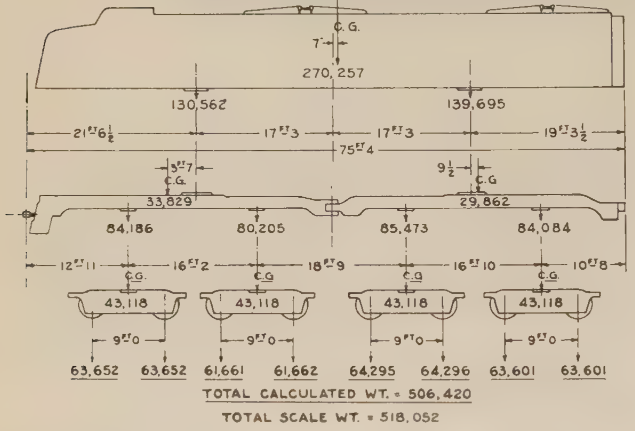
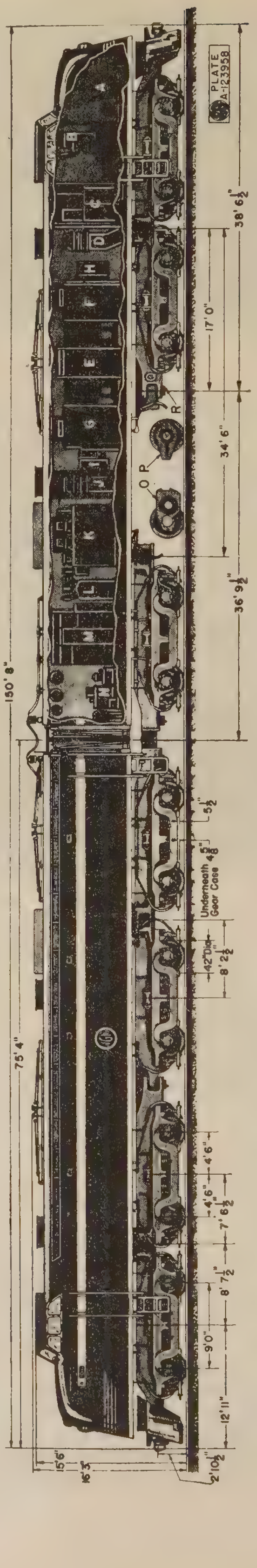


Fig. 12 Final Weight-Distribution Diagram for the Virginian Locomotive

bolster was longer and carried the pilot and draft gear on the extreme end.

A study of the loading diagram indicates the truck arrangement employed to balance these loads. Since the actual expected weight was not known until some time after the design dimensions were fixed, the weight distribution actually secured was remarkably close to calculations, even though a difficult time was encountered with the first locomotive weighed. When it was weighed, there was 10,000 lb weight difference between the



| | |
|---|---|
| A | Motor-alternator set |
| B | Master controller |
| C | Control compartment |
| D | Traction-motor blower unit |
| E | Synchronous-motor (main M-G set) |
| F | Traction generator (main M-G set) |
| G | Traction generator (main M-G set) |
| H | Regenerative exciter |
| I | Main exciter |
| J | Transformer blower unit |
| K | Main transformer |
| L | Oil circuit breaker |
| M | Control compartment |
| N | Air compressor |
| O | Traction motor |
| P | Gear case |
| Q | Span bolster |
| R | Articulation pin (between span bolsters |

Fig. 10 Cross-Sectional Elevation of 6800-Hp Virginian Locomotive

heaviest and the lightest axles. Upon investigation it was discovered that some equalizer springs which were not within the drawing tolerances had been used, and both cab center plates were out of alignment. The final calculated weights and the actual weights secured by weighing are shown in Fig. 12.

Fig. 13 shows the collision structure of the Great Northern locomotive. It is designed to meet AAR specifications for new passenger cars. The sum of the section moduli of both vertical posts and their reinforcement is 66.75 $\text{in.}^3$ Each post has an ultimate shear value of 316,800 lb where it is attached at the bottom to the underframe. The top attachment is designed to withstand a force of 27,800 lb when the post is subjected to a force, sufficient to develop the yield point of the material, of 85,500 lb, 18 in. above the bottom attachment.

These posts are further strengthened by means of plates attached to the top and running diagonally to the side structure at the corners of the front bulkhead, at the level of the window sills. On the outside the contour of these plates follows the hood sheets and provides a connection for the top and side hood sheets. This structure is expected to withstand collision forces within the limits indicated, yielding as the forces increase but absorbing them within limits to protect personnel and equipment. Collision framing with this same stiffness is provided at the front and rear of each of the Virginian cabs.

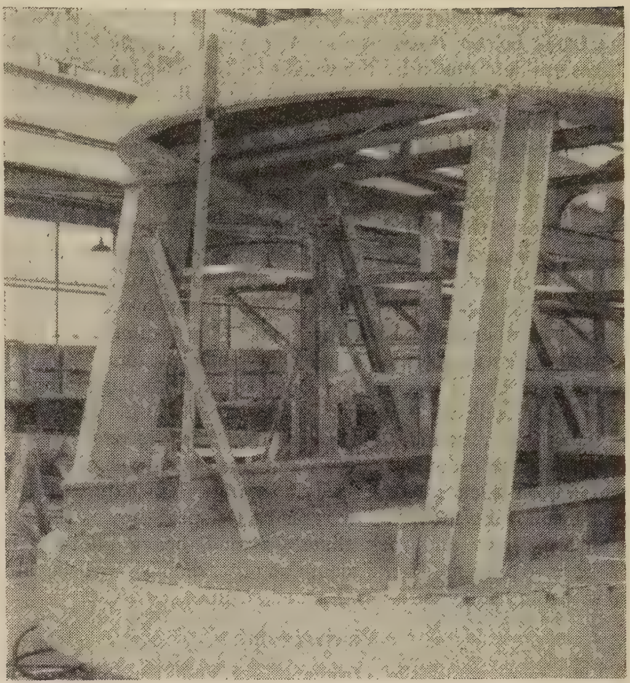


Fig. 13 Collision Post Construction Employed in Nose of Locomotive Cab

### Trucks

Here the two designs are widely divergent. As has been noted previously, the number of axles was determined in each case by the performance specifications and the selection of a particular traction motor to meet speed-tractive-effort requirements. The GE-746 motor rating 500 hp, on the basis of output from the synchronous motor, dictated twelve motored axles on the Great Northern and sixteen (eight per unit) on the Virginian machines.

The use of simple swivel two-axle trucks, supporting span bolsters and cab, was made possible on the Virginian locomotive by the comparatively low top speed specified. Span bolster and truck frames are of grade A unannealed cast steel. The truck frames are supported on double equalizers, which span the journal boxes, by means of helical and semielliptic springs. Loads are proportioned on the springs in the ratio of 65 to 35, respectively. The wheels are rolled steel, class C, 42 in. diam. They are pressed on axles which have $7^1/_2$-in. × 13-in. journals equipped with roller bearings. No restraining or guiding devices were required. All trucks are completely interchangeable in either direction.

Requiring twelve axles to carry the single cab, the design of the Great Northern unit presented a number of new and interesting problems.

In considering running gear and wheel arrangement, the 2—C+C—2 arrangement had been employed a number of times very successfully. It has ten axles but only six drivers. To obtain the required number of drivers with an arrangement similar to this it was necessary to increase the length of the main truck to accommodate four axles instead of three and apply motors to the guiding axles. Such an arrangement is classified as B—D+D—B.

With the wheel arrangement settled, the next problem was to determine the length of the four-axle main trucks. The rigid wheel base of this truck developed to be 16 ft 9 in. long. To accommodate the maximum lateral displacement ($1^1/_2$ in. each way required at the two inside axles on the 17-deg curve), the thickness of the pedestal was reduced at these points in order to maintain identical journal boxes, and a device made up of three layers of rubber vulcanized to intermediate layers of steel on top of each journal box was used. This device was designed to permit the required displacement at a force approximating 10 per cent of the journal load. This force is sufficient to restore the axle to its normal position and maintain stability on a tangent track.

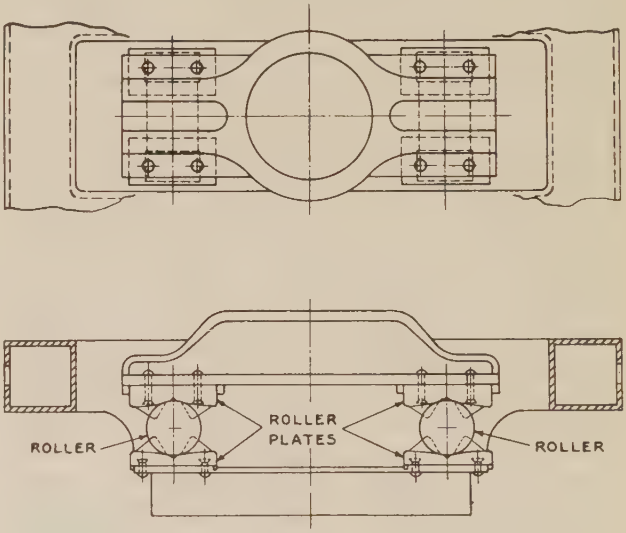


Fig. 14 Guiding-Truck Restraint as Used on The Great Northern Unit

The over-all length of the running gear was approximately 3 ft shorter than the cab, making it necessary to use a drawbar between the main trucks instead of an articulation.

The loading pads required at the rear of each main truck to obtain proper load distribution required loading to 28,100 lb each on four pads.

Motored guiding-truck axles required the same-size wheels and the same load as the main-truck axles. Consequently the bolster and centering devices had to be designed for these loads.

A number of restraining devices were required to guide and stabilize the running gear. Most interesting of these is the guiding truck bolster restraint shown in Fig. 14. The restraining forces are determined by the weight on the center plate and the slope of the roller plates. To guide the main truck around the curves, sufficient resistance is designed into the guiding-truck bolster restraint to slip the leading wheels of the main truck from flange contact with the outside rail to flange contact with the inside rail. Since centrifugal force enters into the calculation of the forces, the final design had to be a compromise between high-speed and low-speed conditions. A spring restraint is used between the guiding truck and the main truck to stabilize the guiding truck on tangent track. Between the two main trucks there is another spring restraint to guide the trailing main truck around the curves. It is designed with sufficient force to slip the leading wheels of the trailing main truck from flange contact with the outside rail to flange contact with the inside rail.

Both the Virginian and Great Northern locomotives are equipped with cast-steel pilots. Fortunately, it was possible to design both truck frames for the same pilot. The nature of these roads, following mountain streams and slopes, subject them to numerous snow and rock slides. Strong, heavy pilots many times have prevented derailment and other damage by being able to withstand and push aside the smaller slides.

### Ventilation

Equipment ventilation always affects, and therefore must be considered in, the mechanical design. The unusual air requirements (100,000 cfm for the Great Northern and 82,000 cfm for a single unit of the Virginian) made evident the seriousness of the problem at the beginning. A factor which led to a solution of this problem was a means for starting the single-phase synchronous motors. It is desirable, because of the power and additional equipment involved in single-phase alternating-current starting, to employ other means of bringing the motor up to approximately half-speed before applying alternating-current power. Means used previously were not considered altogether satisfactory. Further investigation led to the use of a small motor generator set for furnishing starting power. This set, driven by a single-phase 1500-rpm induction motor driving a direct-current generator, could be used to motor the main generators and thereby start the synchronous motor. It could have a very high short-time rating sufficient for main-set starting purposes, and a continuous rating sufficient for control and battery charging during normal operation. In order to take advantage of the simplicity and ruggedness of the induction motor for auxiliary drives, a three-phase synchronous generator was added to the starting set, making it a three-unit two-bearing set, and power was thus secured to operate induction-motor-driven blowers. Combinations of the synchronous-generator and induction-motor poles give the desired blower speeds. In general, a ten-pole generator and four-pole motors to give a motor speed of 3600 rpm have been used. This relatively high speed secures advantages in both space and weight. Another advantage in the use of this system is the simplicity of its control. The generators are designed so that all blowers can be started at once by simply closing the generator-field contactor.

Characteristics of the high-speed axial-flow blower are admirably suited for locomotive applications. Combining high flow and pressure in relatively small space, it has been used to great advantage on both of these locomotives. On the Virginian motive power, where fine coal dust, water, and dirt are a constant menace to electrical equipment; air cleaning blowers, forced ventilation for the main motor generator set, and air taken directly from the outside instead of from the apparatus cab, were specified. A mechanical cleaning device forming the blower inlet was developed and tested. The results indicated as much as 75 per cent efficiency under standard test-code conditions.

Of special significance on the Great Northern electrification is the operation through the Cascade Tunnel. Temperature in the tunnel is practically constant at 55 F. To avoid condensation of moisture on the electrical equipment when entering the tunnel from a colder outside temperature, means are provided for recirculating the transformer and motor generator set cooling air. By recirculating this air, the machine temperatures can be kept above the dew point.

### Air Brakes

Both designs of locomotives employ type 8EL air-brake equipment. Requiring overspeed control, the Great Northern unit uses the KS-8-PB brake valve, while the Virginian locomotive uses the plain K-8-PA valve. The Virginian machines, handling 9000-ton trains, require higher compressor and reservoir capacity than the Great Northern units. Each cab of the Virginian locomotive is equivalent in air-compressor capacity to the Great Northern, having two motor-driven compressors with a total displacement of 300 cfm and reservoir capacity of 75,000 cu in.

Foundation brakes on the Great Northern locomotive are designed to use a single shoe on each wheel. Each cylinder on either side of the truck serves two axles. The same braking ratio (70 per cent at 50 psi cylinder pressure) is used on both the guiding and main-truck axles. A conventional clasp brake is used on the Virginian design. The braking ratio is 75 per cent at 50 psi cylinder pressure.

### Operation of the Great Northern

Since the Great Northern has been operating motor-generator locomotives in its electrified territory since 1926, the new locomotives initiated in 1947, were not novel in so far as type is concerned. As a consequence the introduction of the new locomotives into service involved primarily an extension of well-established operating methods, taking into account the greater ratings and capabilities over the older motive power.

The electrified section of the Great Northern has been described in numerous articles appearing in the technical press (3, 4, 5), and a detailed description of the installation is outside the scope of this paper. It will be well to note here, however, that operation involves gradients of 2.2 per cent and a tunnel approximately 8 miles in length, with the line running through mountainous territory subjected to heavy snowfalls and a temperature range between —20 and +110 F. The profile of the line is shown in Fig. 15.

Preliminary tests on the locomotives indicated a freight-train tonnage rating of 2000 to 2100 tons as a continuous loading on the 2.2 per cent grades. Scaled-weight trains of these tonnages on the 2.2 per cent grades loaded the locomotive traction motors to continuous-rating values, indicating total tractive effort of 123,000 lb at a continuous speed of 15.75 mph. Thus the rail horsepower delivered at continuous rating developed to be 5160 hp. Starting tests on these grades developed adhesions of 26.5 per cent and accelerations were accomplished quite readily without the use of sand on clean dry rail.

With full-rated tonnages, the locomotives are worked at adhesion values approximating 17 per cent on tangent track with dry rail, and there appears to be little, if any, tendency for driving wheels to "creep" under these conditions. Some creep is experienced in entering and leaving curvature. With poor rail conditions some creep with no attendant loss in train speed is experienced on tangent track. In heavy curvature, however, the degree of creep encountered results in train-speed loss of 1 to 2 mph. Average all-weather running adhesions of 15 per cent to 16 per cent on track, involving curvature of 8 deg to 10 deg, have been found to be practicable.

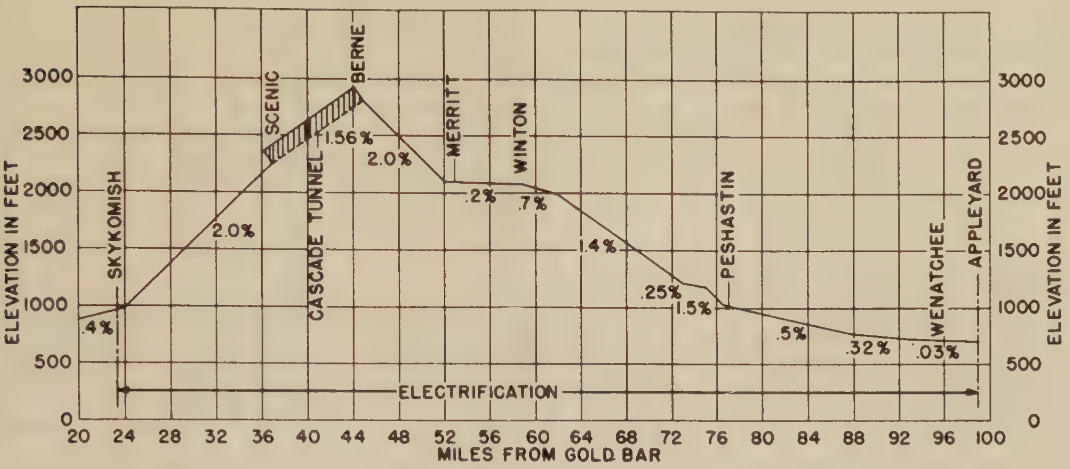


Fig. 15 Condensed Profile of Electrified Section of The Great Northern Railway

No noticeable differences in operable adhesion values as affected by driving-wheel diameter have been observed. The new locomotives have 42-in. drivers while the older machines have 55 to 56-in-diam driving wheels.

The extreme fineness of control afforded in both motoring and regenerating operations permits the ready use of the new locomotives in freight trains with any type of motive power operated, be it steam, Diesel-electric, or the older types of motor-generator electric locomotives. Heavy freight operations involving trailing tonnages of 5000 tons are worked with locomotives at the head end, in the middle and at the end of the train.

Passenger trains with consists of 14 to 17 Pullmans and a heating tender (the locomotives are not equipped with train-heating boilers) are handled up to speeds of 50 and 60 mph consistent with track limitations and passenger comfort.

While the motor-generator locomotive is basically a constant-horsepower machine, lending itself nicely to the practice of peak-demand control by power dispatchers, it can be overloaded for short times as occasions and emergencies demand. Rail horsepowers approximating 5800 have been secured on occasion from the new locomotives.

Power-factor control of the supply system is readily obtained by manipulation of the synchronous-motor excitation on all of the motor-generator motive power. Unlike the Virginian Railway operation, no induction-motored locomotives are operated, and the maintenance of unity to 0.95 leading power factor on the system is readily accomplished.

The efficiency of operation measured in terms of gross-ton-miles per hour seems to be somewhat better for the new locomotives than for the older units. A figure of 6.8 gross-ton-miles per hour per kilowatt at the substation on a 2.2 per cent grade holds for the new machines compared to 6.2 gross-ton-miles per hour per kilowatt for the average performance of the older machines. Undoubtedly, this is due in part to the lesser weight per horsepower of locomotive 147 lb applying to the new locomotives, compared to 180 and 203 lb for the older machines. The new locomotives have all the weight on the drivers.

The use of the B—D+D—B running gear with four motored axles in each of the main-truck frames gave rise to some question as to the effect the locomotives might have on the track structure. Observations during initial operations indicated that good tracking was being secured over the whole range of speeds operated. However, shortly after operation had commenced, some sections of track were reballasted in routine maintenance, and complaints developed that the locomotives were moving track in sharp curvature.

Measurements were made which indicated no deflection at speeds above 30 mph. However, at speeds of 10 to 15 mph permanent deflections of the track toward center of curvature, as much as $^1/_2$ in. were recorded, when drivers Nos. 3 and 10 moved by the recording point. These observations indicated that the initial resistance (24 per cent) of the variable-resistance centering device was too high. Pending installation of new roller plates, temporary relief was secured by removing the wear plates from the journal boxes and pedestals on drivers Nos. 3 and 10 which increased the lateral to approximately $1^1/_2$ in.

New roller plates were supplied which reduced the initial resistance to 18 per cent, building up to 20 per cent in the first inch. With these changes, the locomotives have been operating satisfactorily.

Some interesting observations of the added train resistance occasioned by the "piston action" of trains in long tunnels have been made. Comparing train-power demands, as indicated by the locomotive metering equipment, approximately 7 per cent more power in motoring is required to move a train against the tunnel grade than is required for operation at the same speeds on open grades of the same severity. The amount of regenerated energy is affected to the same degree, and less energy is required to hold a train at given speeds in the tunnel than is required for similar grade and speed conditions in the open.

Observations involving the added train resistance occasioned by 4 to 6 in. of snow on the tracks indicate an increase of resistance of approximately 15 per cent.

A minimum of rail sanding is employed since tests indicate that train resistance may be increased by as much as 10 per cent by the over-liberal use of sand in making train starts with heavy trains on heavy grades.

## Operation on the Virginian

The electrified section (9) of the Virginian's lines extends eastward from Mullens, W. Va., to Roanoke, Va., a distance of 134 miles, traversing heavy mountainous territory crossing the Appalachians with a maximum ruling grade eastbound of 2.07 per cent. The profile of the electrified section and data pertinent thereto are shown in Fig. 16. The line is single-tracked with the exception of 22 miles of double track eastward from the Mullens terminus. The 11,000-volt 25-cycle single-phase system was installed in 1925, and, until the recent acquisition of motor-generator locomotives, has been operated with two-speed (constant speeds at 14 and 28 mph) 6000-hp induction-motored locomotives (10).

The two-speed induction-motored locomotives were entirely

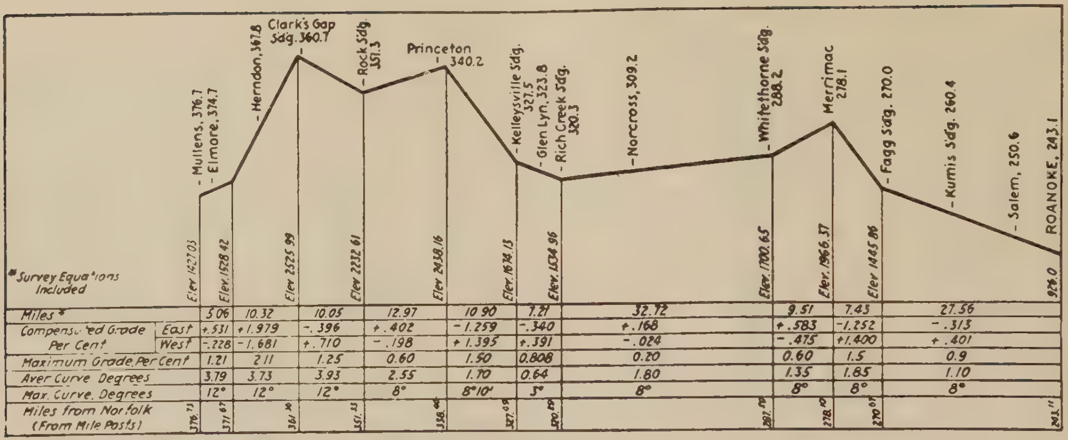


Fig. 16 Condensed Profile of the Virginian Railway's Electrified Section Between Mullens and Roanoke

satisfactory for heavy tonnage movement, but there was a substantial development of time freight business through the years, and when additional power was considered, it was decided that a variable-speed locomotive would be the most practical supplement to the locomotives in service. The basic operation for which motive power is designed is the eastward movement of 3000 tons per locomotive from Elmore to Clarks Gap, a fill-out to 9000 tons at Clarks Gap, and the completion of the run with 9000 tons per locomotive from Clarks Gap to Roanoke. The induction-motored locomotives satisfy these requirements, and the motor-generator locomotives were purchased for the same service demands, for operation singly or doubled with the older motive power. The four motor-generator locomotives secured from General Electric were delivered early in 1948, and have in their operation complied fully with the functional specifications.

The motor-generator locomotive has a very large number of running-control steps available through the relatively fine generator-field control and various combinations of series and separate excitation of traction motors. This permits accurate control of acceleration and regenerative braking, the acceleration control making for ease of operation when doubled with the constant-speed locomotive, and regeneration control greatly reducing and, with certain tonnage and grade combinations, even eliminating the need for air-braking.

Voltage and power-factor conditions on the contact system have been improved as a consequence of the synchronous motors utilized for main-set drive in the new locomotives. Unity or near-unity power factor is secured through control of motor excitation.

Some trouble was experienced with the appearance of excessive voltages on the secondary side of the locomotive transformers, coincident with operation of the 11,000-volt oil circuit breakers on the high-tension side. Normal secondary-voltage supply to the synchronous motors is 1550 volts, and synchronous-motor contactor supporting insulators normally rated at 10,000 volts were breaking down under these conditions. Klydonograph tests indicated the presence of surge voltages with peaks as high as 16,000 volts—a ratio of 10 to 1 over normal steady-state voltage conditions. The installation of resistance contacts on the oil circuit breakers, and capacitors on the primary side of the transformers served to hold the surge voltages within acceptable limits.

The main motor generator sets developed resonant-frequency phenomena, first manifested in shaft-coupling troubles. It was developed that the natural period of torsional vibration of the rotating structure of the locomotive motor generator sets occurred within the single-phase power pulsation frequency (normally $2 \times 25 = 50$) of the supply system, and that in passing through or operating at certain system frequencies, the rotating masses were being subjected to excessively high torsional stresses. The phenomena first became apparent in loosening of the couplings and "fit" corrosion of the coupling bolts between the synchronous-motor and generator shafts. Further investigation developed that the high torsional stresses had fractured the outside dovetails in the synchronous-motor field punchings and end castings, where these dovetails fitted into the retaining slots in the shaft forging.

The natural frequency of the rotating systems was changed to a value of approximately 39 per sec—well below a value corresponding to the minimum frequency experienced on the power-supply system—by reducing the diameter of the synchronous-motor shaft in its bearings from 10 to 9 in. Entirely successful operation has been secured subsequent to this change in shaft dimension.

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# Discussion

P. H. Hatch.[6] There are two principal types of electric locomotives for use on 11,000-volt a-c systems. One makes use of the alternating-current series commutator motor, and the other the direct-current series motor. For traction circuits the former uses a step-down transformer with a number of secondary taps to provide the range of voltages required for acceleration and running; the latter uses a step-down transformer with a minimum number of secondary taps for supplying proper voltage for the synchronous motor which drives the direct-current generator. From the standpoint of amount of major equipment and control required, the locomotive using the alternating-current series traction motor is the simpler. The offsetting feature, however, of the motor-generator type of locomotive is its use of the standard railway type direct-current series traction motor.

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[6] General Mechanical Superintendent, The New York, New Haven, and Hartford Railroad Company, New Haven, Conn.

Granted that both types of locomotives can be built to produce the general operating characteristics required, the long-range factor of cost of maintenance and cost of operation in respect to power consumed must be considered.

While the modern motor-generator locomotives described in the paper are too new as yet to judge what their maintenance cost will be, nevertheless, it would be reasonable to suppose that over the life of the locomotive it would be higher for the motor-generator type than for the other type. Certainly it would be interesting and valuable to follow this feature in connection with these locomotives.

As to the power-consumption question, it would be expected that the motor-generator-type locomotive would entail more losses than its alternating-current traction motor counterpart, though admittedly this particular feature would be in some degree offset by power-factor correction.

Certainly the experience of the New Haven Railroad with motor-generator-type freight and switching locomotives, starting in 1926, points to the significance of both of these questions of maintenance and power consumption.

The authors have done a fine job of describing the design and operating characteristics of the latest motor-generator-type locomotives built for the Great Northern and the Virginian Railways, and it is hoped that a companion paper of equal merit will be prepared covering the actual operating and maintenance experience of these locomotives over the period culminating in their first major overhaul.

Charles Kerr, Jr.[7] In the heavy-grade territory served by the Great Northern and Virginian railroads, the type of power described in the paper should give a good account of itself.

The authors make a strong case for the advantages of low voltage direct-current traction motors. These advantages are not denied. However, it is thought that credit might be given to improvements being made in locomotives equipped with alternating-current traction motors. In this connection, the following comparison is given between the two motor-generator locomotives discussed in this paper and locomotives now under construction for the Pennsylvania, equipped with alternating-current traction motors:

| | Great Northern | Virginian | Pennsylvania |
|---|---|---|---|
| Trolley voltage | 11000 | 11000 | 11000 |
| Frequency cycles.......... | 25 | 25 | 25 |
| Maximum speed, mph..... | 65 | 50 | 65 |
| Locomotive weight lb...... | 735000 | 1033832 | 540000 |
| On drivers, lb........... | 735000 | 1033832 | 540000 |
| Continuous hp............ | 5000 | 6800 | 5625 |
| Maximum hp............. | 5800 | ... | 7500 |
| Continuous tractive effort, lb.................... | 119000 | 162000 | 90000 |
| Ratings per 100 tons on drivers | | | |
| Continuous hp.......... | 1361 | 1361 | 2084 |
| Maximum hp........... | 1578 | ... | 2777 |
| Continuous traction effort, lb.................. | 32370 | 31340 | 33330 |

For equal driver weights, the Pennsylvania locomotive with alternating-current motors produces a maximum tractive effort equal to the MG type. At speeds, it produces greater horsepower for the same weight, making a more versatile locomotive for territories where both drag and high-speed service may be encountered.

Any railroad, using the alternating-current system, can be assured of excellent motive power with locomotives of the MG type, or with those using alternating-current traction motors.

T. M. C. Martin.[8] Motor-generator locomotives are virtually without peer in western mountain-grade applications. Hence the writer is somewhat at a loss to understand the reasons why motor-generator locomotives are so greatly underrated by the motive-power fraternity. It would seem that they are deserving of much more attention and respect than they customarily receive. In spite of this paper, and its apparently enthusiastic support by equipment-manufacturing personnel, nevertheless, the impression exists that the motor-generator locomotive is not openly espoused with great joy by the builders. It is said to be the most expensive type to build. The writer is not in a position to say, but does believe there may be economic reasons to support a somewhat higher first cost.

The apparent recipient of the builders' most extravagant praise in recent years is the straight alternating-current series motor locomotive similar to the Pennsylvania's GG-1 class. Although it is freely admitted that, as originally conceived and built, the GG-1 could not fulfill the requirements of "laying-up" against the load in mountain-grade operations without benefit of armature rotation, as described in the paper, there seemingly is agreement that a locomotive of the series alternating-current type can be built that will equal the performance of the motor-generator type in this respect. There are rumors that such a locomotive is even now being erected.

Be all this as it may, and the writer does not wish to be recorded as a scoffer on the basis of the possible physical performance of a series alternating-current locomotive, it occurs to him that there would still be two or three characteristics peculiar to the motor-generator type that would clothe it with definite superiority over other electric locomotives.

Consider, for example, power factor. If it be assumed that a series alternating-current type locomotive would have an average operating power factor of about 0.8 lagging, it is evident that a unit of continuous output rating comparable to the Great Northern's 5018 class motor-generator type would have the approximate 5-4-3 right-triangle relationship of 5000 kva, 4000 kw, and 3000 rkva.

Even to approximate the Great Northern 5018 class, such a locomotive should be equipped with capacitors capable of supplying at least 3000 rkva. The placement of perhaps 1500 cu ft of capacitors, together with their control apparatus on the locomotive, might require some little ingenuity. It may be doubted that such a locomotive could be brought up to unity, much less leading power factor anywhere near as easily or economically as it is accomplished automatically in the motor-generator locomotive.

Next is the matter of regenerative braking. It is generally agreed that the motor-generator locomotive is the ideal type for regenerative braking. We may disregard the operating advantages of regenerative braking since the series alternating-current type could be provided with a dynamic brake that would be almost, if not quite, as good.

What cannot be brushed aside lightly is the economic waste involved in dissipating valuable electric energy unnecessarily in resistance grids when it might be returned to the line to serve useful purposes elsewhere. Evidently most engineers do not appreciate fully the economic value of regeneration on western railroads, and the writer would like to develop this subject briefly with respect to Great Northern operations.

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[8] Electrical Engineer, Bonneville Power Administration, United States Department of the Interior, Portland, Ore.

In terms of present utilization on the Great Northern, the 5018 class is able to approximate only 1.5 round trips or 225 miles per day. This is about 80,000 miles per year—not a particularly impressive figure. In freight service with about 2400 gross tons, including locomotive, this is equivalent to about 192,000 kgtm[9] per locomotive per year. On the present Great Northern electrified zone, the gross energy consumption (motoring) will be about 50 kwhr/kgtm, the regeneration will be about 10 kwhr per kgtm, making a net consumption of about 40 kwhr/kgtm (all energy figures are as of 3-phase, 60 cycles supply points).

The value of regeneration then is about 1,920,000 kwhr per year, which, at the present rate schedules in effect on the Great Northern (fractionally in excess of 1.0 cent per kwhr) amounts to about $20,000 per year per locomotive.

Lest this appear to be too special a case built around a relatively high proportion of heavy-grade operation, let us suppose that the Great Northern electrification is extended both ways from present termini until it includes the entire main line from Seattle to Spokane, some 330 route miles. In this event, individual locomotive mileage could quite easily be brought up to 500 per day or 180,000 miles per year. It is estimated that motoring and regenerative energy would approximate 32 kwhr and 4 kwhr per kgtm, respectively. The locomotives would now be handling 2400 × 180 or 432,000 kgtm per year. At 4 kwhr/kgtm this would mean an annual total of 1,728,000 kwhr of regenerative energy, having a value of some $18,000 per year at present Great Northern power rates.

The Great Northern examples cited are believed to be entirely typical. Most sections of western main line that are economically feasible of electrification have profiles embodying sufficient regeneration potentialities to warrant adoption of motor-generator-type locomotives for economic reasons alone. Even if present electric power rates are cut in half, it seems evident that not less than $10,000 can be saved per locomotive per year through utilization of regeneration. Couple this with the ability of the motor-generator locomotive to produce rather than use reactive power, and another 20 per cent saving can be claimed annually. The potential savings from these two factors would appear to run from $12,000 to $24,000 per locomotive per year, depending upon the basic rate schedules under which electric power is purchased. If money is assumed to be worth, for example, 6 per cent, this is equivalent to saying that a railroad can afford to expend from $200,000 to $400,000 more per locomotive for motor-generator locomotives even if it is believed there are no other reasons for preferring them. It wouldn't appear that they need to cost this much more per unit to build, and, as the authors have shown in this paper, there are many important reasons why motor-generator-type locomotives are superior.

It would appear to the writer that before a railroad purchases alternating-current series motor-type locomotives of clearly inferior characteristics as regards power factor and regeneration capabilities merely on the basis of lower initial cost, it should understand fully that it is probably going to be paying a very substantial premium in the form of higher operating costs. It can be demonstrated that in the case of most western railroads, the differential savings resulting from the operation of motor-generator locomotives will support a much higher initial cost for such locomotives should this be found to be really necessary.

J. Stair, Jr.[10] For the profile and train movements encountered on the electrified sections of the Great Northern and Virginian Railways, the motor-generator type of locomotive appears to be well-adapted. The present paper covers the situation admirably.

It would add to the value of the paper, as a permanent record, if "speed-traction effort" and "speed-braking effort" curves were included for the latest class of electric locomotive on each of these railways.

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[9] kgtm = thousands of gross-ton-miles.

[10] Electrical Engineer, The Pennsylvania Railroad, Philadelphia, Pa.

# Two Slants on Postwar Wood Finishing

## Part I—Current Practice

By P. S. KENNEDY,[1] NEWARK, N. J.

**The postwar period has witnessed much activity and growing interest in the finishing of wood. This has been due to the following factors: (1) The ever-present objectives of greater speed and reduced cost. (2) The desire for better and more resistant finishes. (3) Increasing recognition that ultimate cost, rather than package cost, should be the yardstick of value for finishing products. (4) The vital need for a quick and consistent method for anticipating the check resistance of lacquer films, in particular. This trend has been accentuated by unusual circumstances. These aspects of current conditions in the wood industries are treated in this paper.**

### Greater Speed and Reduced Cost

In line with general experience, the postwar period has included a seller's market in the wood industries, together with radical increases in labor cost. Accordingly, aims have been to produce finished units rapidly, plus all possible economies.

Probably the sorest spot in wood-finishing materials is the filler which must be applied on open-grain woods such as mahogany, walnut, and the like, and intensive activity has been directed to a cure. In the prewar period, filler was generally regarded as a necessary evil, as well as a staple product to be purchased at a staple price, like flour or sugar. It was relatively slow drying—overnight being the usual minimum drying period—but in addition, subsequent performance was unpredictable—particularly with lacquer finishes. Various deviltries developed periodically, the most poignant of which were the so-called "graying of pores" and an unsightly "muddying"—usually in sections—of what should properly be a uniformly clear transparent-film effect.

One of the most constructive results of this postwar experience has been the growing appreciation by the consumer that the established practice of buying filler "at a price" could be shortsighted. When one of these epidemics of graying of pores, or muddying of films was encountered, the corrective labor expense invariably produced a staggering ultimate price tag. Sufficient consumers adopted this line of reasoning to encourage the finish manufacturer, for the first time, to spend time and money on the development of filler, with the assurance that a successful effort would receive a just return.

A receptive attitude was also created toward tolerance of change in long-standing shop practice for the handling and application of filler. For instance, a new filler development, because it had to be handled faster, might require two men to wipe off a large unit, rather than one man. Actual man-hours would be the same, however. Again, a new filler development might not suspend as well after reducing for use, and thus require an occasional stirring which would not have been necessary with the older type.

Thus fillers have come into use, employing various synthetic vehicles, as contrasted with the long-accepted linseed-oil vehicle, and drying time, not only shortened to periods such as an hour, but also giving better clarity, which is another way of saying "proof against pore graying and muddied films." The ultimate in this direction has been achieved with the stain-filler combinations, employing fast-to-light dyes. The best of these products not only give "tops" in clarity; but they are absolute proof against pore graying. The explanation for this is that the translucent inert pigments, used in the filler, are themselves actually dyed. They therefore do not "dry out" or "wash out" to an unsightly pore condition.

Particularly in fast production, such as radio cabinets, operators, who have been open-minded in adjusting labor practice to conform with the product, have been able to effect important economies by the elimination of both material and labor costs. For example, a good-quality finish, employing stain and filler separately, first calls for the material and operation of applying a coat of stain. Next, a sealer wash coat of either lacquer or shellac of low solids content, followed by a scuff-sanding operation. The purpose of this is to seal the pores so that when the filler is subsequently applied some of its vehicle is not sucked away by stray capillaries in the wood, robbing the full strength of the filler, as well as giving "smeary" pore effects at such points.

With a stain-filler combination, all of this is combined into a single operation with a single product. But while, from this point on, the application of the top coats would be identical, the danger of graying still exists with the simple filler. Sometimes precaution is taken against this by formulating so that the filler is tinted with so-called oil-soluble anilines. When the top-coat material is applied, these anilines "bleed" and in so doing stain the inert pigment. The objection to this is that it is a temporary measure, as these colors are not fast to light and may subsequently provide embarrassment. Another method of obviating against graying is the application of a shading stain over all. While this tends to color over potential gray pores, it is at some sacrifice of finish clarity, plus being an additional operation.

In all frankness, it must be admitted that these so-called fast fillers and stain-filler combinations, are not as foolproof as the old-fashioned filler for wiping and cleaning up; nor for packing the pores quite as full. But the good ones do a most acceptable job, as the mechanic gets the hang of them. Supplemented by the continuing laboratory work of the maker, further improvements and refinements are being progressively achieved.

The best of these synthetic types of fillers do not "heave" like the old-fashioned filler. This is temporary "lifting" from the pores, which occurs when top-coat material is freshly applied, and gives the illusion of a most flushly filled job. Unfortunately, there is a subsequent collapsing which shows up as "shrinkage." The best of synthetic fillers frequently look "hungry" by comparison because they are not so affected by freshly applied top coat, with the pore filling remaining fixed. With the continued support and co-operation of the user, the future outlook for filler is most promising.

Another angle of reduced cost applies most specifically to lacquer jobs. From the standpoint of speed, saving of floor space,

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Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—WDI-2.

and fast and easy touch-up and repair, lacquer is the ideal finish for wood. But it does have the shortcoming of what might be termed low solids or film thickness.

There is a definite limit to the amount of solids which can be incorporated in lacquer and still maintain a suitable spraying viscosity. Roughly speaking, varnish will have twice the solids or double the film thickness of a lacquer coat. Much work has recently been done to improve this deficiency in lacquer, and along two lines; one by increasing the solids content of the lacquer, and the other, by hot-spray application. While both of these measures have proved effective, from the standpoint of giving possibly a 50 per cent increase in film thickness over what is regarded as normal (a 21 per cent lacquer) sufficient resistance and objection have developed to prevent general adoption.

A resultant trend has been to secure the desired film thickness by means of synthetic coatings—of which alkyd-urea base compositions would be typical—and these are currently finding some usage. The cure of these coatings is activated by means of a catalyst, and while some are available in air dry form, most of them require stimulation by heat. The average temperature ranges employed are between 130 and 135 F, as there is a pronounced feeling that in exceeding that maximum temperature vagaries of wood and glue are apt to cause complications. However, on some current government furniture work, specifications call for 150 F.

Best and surest satisfaction is secured by adding the catalyst to the coating just prior to the time of use; although some of the products are supplied with catalyst added. In this connection, there is always a question of package stability, and potential difficulty exists if the user does not have a rigidly enforced system of first using up the oldest finishing material on hand.

Investigation by finishing manufacturers is currently under way with various kinds of synthetics, and further developments can be confidently expected with synthetic clear coatings.

### Better and More Resistant Finishes

The advent of the synthetic finishes, besides affording savings because of heavier film thickness, introduces varying degrees of resistance, which are highly interesting from the sales and service angle. When cured, many of them have outstanding resistance to alcohol and many other materials which affect lacquer and ordinary varnish films.

The maximum properties in these finishes are secured when the work is top-coated entirely with these coatings. But for various shop reasons there is quite a general trend toward using an undercoat of lacquer-type sealer, followed by a top coat of the synthetic. Importantly involved in this is the economy in sanding and the avoidance of possible "shelving" of coats of the synthetic itself when the cure of the undercoat has been carried too far to permit of proper knitting between the coats.

Here again, however, this is a matter amenable to ready control in a well-regulated finishing room, because it is possible to get satisfactory sanding on undercoats of synthetic, and to provide against too complete curing of undercoats.

### Ultimate Cost Versus Package Cost

There has been a decided and significant increase in the application of accounting practice in wood-finishing departments to more careful and detailed segregation of costs. In these instances the package or container cost of finishing products is no longer the prime consideration, and many revealing instances have occurred as the result of teamwork between the purchasing agent and the finishing superintendent.

Actual mileage is not necessarily the most important factor. Hospitalization—or touch-up and repair—is frequently the most potent figure. Accessories, such as sandpaper, cost real money these days, but are too often taken for granted, rather than investigated from the angle of whether much less would be used with another finishing product. Savings in sanding, rubbing, and polishing time all add up to the careful scrutiny which is being given, more and more, and the net importance of which cannot be overemphasized.

### Quick Method of Testing Lacquer Films

The rugged winter of 1947–1948 not only accentuated the need of a greater margin of safety for lacquer films, but for a quick method of evaluating them. To be factual, the blame for the widespread finish failures should not be laid entirely to the finishing materials—specifically lacquer. Because of rush and shortages, much lumber and veneer were used, which were not in normal condition, to say the least, and the stresses and strains which they created placed an undue load upon the lacquer coats.

However, it emphasized a fundamental deficiency in formulations to meet abnormal conditions—not only weather like 1947–1948, but changes in merchandising conditions. Typical of these would be warehousing of finished products, which will increase importantly. It is well known that ordinary lacquer films lose check resistance on standing; so there is the double problem of pronounced improvement in lacquer films, and a practical method of measuring their strength.

The present accepted methods for so-called "cold check" are not only time-consuming and expensive, but undesirably open for error. Hence a radical correction of this situation would be of such dynamic importance that the companion paper which follows as Part 2 warrants thorough consideration.

# Two Slants on Postwar Wood Finishing

## Part II—Suggested Method for Predicting Check Resistance of Lacquer Films

By W. T. SMITH,[1] NEWARK, N. J.

**This paper presents details of equipment and technique for performing control tests on film-forming materials. Typical tests are interpreted and correlated, and illustrated examples are given of test results on various lacquers.**

THE tendency of clear, lacquer-type furniture finishes to fail by severe checking or cracking, especially under exposure to wide and abrupt changes in temperature, has long resisted accurate and significant laboratory prediction and control. In an effort to perform control tests of the film-forming media, carefully controlled and presumably representative wood panels are prepared, aged for a period of up to 2 weeks and then subjected to a systematic cycle of temperature extremes in an effort to establish the limits of check resistance of the finishing system in question.

Distinct stresses are set up in a cellulosic film in the process of setting. This effect is influenced by the nature of the incorporated resin as pertains to solvent release and basic molecular arrangement, the viscosity of the cellulose, and the thickness of the film. The actual moisture content of the film itself, especially in the presence of alkyd resins and/or vegetable oils, is a directly pertinent influence on tendencies to check at low temperatures. It is indicated by Koenig[2] that mechanical failures such as checking and cracking are rupture phenomena, and the result of external and/or internal forces. These phenomena are influenced by nonuniformity of the film or the substratum which leads to local stresses.

Checking of lacquer films is due to three factors, as follows:

1 The deforming force.
2 Nonuniformity of the film.
3 Local stresses exceeding the film strength.

Deforming forces may be caused by changes in the substrate. Moveover, the film may undergo contraction on aging, and this may lead to stresses and strains in the film which are dependent upon the mechanical properties of the coating. The solvent will evaporate from the lower layers much more slowly than from the outer layers. Consequently, the stresses in the outer layer will grow more rapidly than in the lower layers, reach a maximum value in the surface layer, and decrease in the direction of the substrate. However, as the drying and aging proceed, the distribution of stresses will become more uniform. Shrinkage takes place at a measurable rate for a period of 30 days or more and, together with progressive development and relief of stresses, is not confined to a short time interval. When films dry and age, shrinkage occurs, which results in deformation and causes stresses. The theoretical examination of the mechanical processes taking place during film formation indicates that stresses occur even while the film dries.

### Wood-Panel Tests

Variation has long been a persistent attending factor in the performance of wood-panel tests for cold-checking tendencies of lacquer systems. In an effort to identify the variables influencing the result of wood-panel tests, an evaluation of a representative furniture-finishing system was made by finishing large plywood specimens and cutting them later into smaller test pieces in an attempt to minimize wood source variations. The tests were performed on specification panel stock, especially constructed and furnished for test purposes. This panel stock consists of a $^5/_{32}$-in. yellow-poplar core, $^1/_{28}$ or $^1/_{30}$-in. yellow-poplar crossbanding, and face and back of mahogany and sap gum, respectively, of about $^1/_{32}$ in., to make up a $^5/_{16}$-in. resin-bonded panel.

The lacquer system involved is of the conventional radio-cabinet type, consisting of the following:

1 Non-grain-raising stain.
2 A light cellulosic wash coat.
3 A paste filler.
4 A 20 per cent nonvolatile sanding sealer.
5 Two coats of a 21 per cent clear rubbing-type finishing lacquer.

This single representative system was used in all tests described herein.

The cold-check cycle referred to consists of the conventional 1 hr at 120 F, followed immediately by 1 hr at —5 F to complete each cycle. Inspection is made at an oblique angle in strong light after each cold period.

### Conclusions

1 The major and basic conclusion evident here is that wood-panel tests for cold-check tendencies in any normal scope of handling and condition are rampantly inconsistent.

2 The moisture content of the wood at time of finishing, especially within the range of conventional precision woodworking practice, is not a significant factor to a consistent degree.

3 Moisture sealing of the wood member on all unfinished surfaces has the effect of causing a slight increase in resistance value in isolated sections, but causes a somewhat wider spread of results to the end of increasing the inconsistency of the test results.

4 Moisture conditioning of the finished member by storage in varying conditions of relative humidity is the most influential factor observed here. Variation of moisture content of the finished member—wood and finish—from 5 to 10 per cent moisture content, will effect a variation in check resistance of from 500 to 800 per cent.

5 While the combined precautions of moisture conditioning and moisture sealing will, in a majority of cases, prove slightly

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[1] Supervisor, Physical Testing Laboratory, Finishes Division, Interchemical Corporation.

[2] "Shrinkage and Deterioration of Paint Coatings—Part I," by W. Koenig, *Paint, Oil and Chemical Review*, 111, No. 19:15, September 16, 1948.

Contributed by the Wood Industries Division and presented at the Wood Industries Division Meeting, Jamestown, N. Y., September 27, 1949, of The American Society of Mechanical Engineers.

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better than moisture sealing alone, this result is not completely consistent.

6 Checking results cannot be assigned to any continuity or relationship of wood structure, even in adjacent sections of the same original stock.

7 It must be concluded that wide variation in results on wood test panels may be expected from unpredictable, natural variations in wood density, structure, and composition, over and above the demonstrated sensitivity to handling and ambient condition, to the extent that it is not practical or feasible to evaluate the checking tendencies of an organic-finish film conclusively by this method.

## Film Tests on a Metal Substrate

The most exhaustive study of cold-check evaluation on the media of wood surfaces will serve mainly to emphasize the number and complexity of variables present, or potential, in a wood substrate. Such are these variables and vagaries of behavior that they cannot all be measured, classified, or even recognized. In setting out to evaluate the unknown checking potential behavior of a finish film on a wood surface, we are employing an unknown element over a substrate of a similarly unknown and unpredictable nature. In order to permit equitable measurement of a potential value in a material of unknown behavior, an accompanying medium of known and controllable properties is indispensable. Constructive thinking in various fields has led experimenters toward the employment of such constants.

C. W. Smith[3] states that stress lacquers have long been used as a surface indicator to show, by induced checking, the presence of stress lines in the body of the substrate under scrutiny. Stress lacquers are specially formulated brittle materials of a known and controlled behavior as pertains to tolerance of lateral stresses. Castings and similar metal parts are coated to a thickness of from 0.0003 to 0.0008 in. with these lacquers and subjected to heavy operational stress and strain in suitable testing apparatus. By the nature and direction of the resulting fracture lines in the brittle coating, the stress reaction of the substrate in question may be observed and evaluated.

Since checking failure of wood finishes is the result of an inability of the surface coating to cope with dimensional changes in the substrate, it would seem to follow that systematic controlled manipulation of an amenable substrate would permit the assignment of a specific resistance to the finish film under scrutiny.

Attempted manipulation of the substrate is the principle involved in conventional wood-panel checking tests, but the direction and extent of the induced dimensional change cannot be controlled or predicted in other than very general terms.

An applicable substrate may be found in the form of very thin sheet copper of known and specified temper and ductility. When such a surface is coated with the film under test, the sheet and the film together may be deformed systematically under hydraulic pressure to form a "dimple" or hemispherical section, the surface area of which represents a measurable increase or distention of its original dimensions.

If the film is cured to a constant state, the distention performed at controlled low temperature and the distention on the radius of the spherical section measured to 0.0001 in., the actual substrate expansion at the point of fracture failure of the film may be expressed to an accuracy of 0.1 per cent.

Small[4] states that film flexibility, as evidenced by cold-check failure, may be correlated with elongation data, and that there is a striking correlation between cold-check resistance and the degree of elongation. Comparison of values so obtained on standardized formulations, on which cold-check data from wood-panel tests, as well as from field applications, have been accumulated over a period of years, serves to correlate results of the distention method with those obtained on wood surfaces. Such comparisons also serve to indicate the limits of movement of conventional wood surfaces in terms of per cent of area increase and lead to the conclusion that finish failures on wood surfaces are avoided by maintaining a standard of distention potential, at low temperature, at a level offering a margin of safety over the range covered by the behavior of wood.

In so calibrating the "distention-potential test," a series of thirty materials was used, the relative cold-check resistances of which, in terms of hot and cold cycles, have been well established. The distention potentials of these materials fall, Table 1, into well-defined groups or fields which have been designated arbitrarily as Classes I to IV inclusive. The accuracy of the distention factor as a criterion of checking potential has been found to be such that a specific formulation will not fall out of class unless there has been error in compounding. Repetition of tests of the same lot of material show an operational aberration in result of between 5 and 10 per cent only.

TABLE 1 CLASSIFICATION OF 30 REPRESENTATIVE LACQUER FORMULAS BY DISTENTION-POTENTIAL TEST

| | Class IV | Class III | Class II | Class I |
|---|---|---|---|---|
| Tolerated distention | Not over 0.0700 | 0.0700 to 0.0850 | 0.0850 to 0.1000 | Over 0.1000 |
| Per cent increase in area | Not over 1.4 per cent | 1.4 to 2.3 per cent | 2.3 to 2.8 per cent | Over 2.8 per cent |
| Considered | Poor | Fairly good | Good | Excellent |
| Approximate cycles—Wood | 3 or less | 8 to 10 | 15 to 18 | Infinite number |
| *Sealers* | | | | |
| Under 21 per cent.... | | | | 4 |
| 21 to 25 per cent..... | 1 | 3 | | |
| Over 25 per cent...... | 2 | | | |
| *Lacquers* | | | | |
| 21 per cent solids..... | 8 | 5, 6, 7, 17, 18 | 21, 22, 23 | 9, 10, 11, 12, 13, 28 |
| 25 per cent solids..... | 16 | | 24, 25, 26, 29 | |
| 28 to 30 per cent..... | 14 | 19, 30, 20 | 27 | 15 |

Routine control methods of this test are such that by use of a standardized substrate and controlled coating and curing methods it is possible to make an accurate cold-checking evaluation within an elapsed time of 24 hours after the sample is received in the laboratory.

## Preparation of Specimens

Choice of coating methods of the copper specimens is limited by the flimsy and flexible nature of the thin sheet which is 0.0050 in. ±0.0004 in. The most convenient and practicable method of coating was found to be by controlled pour or flowdown. A 7-in. length of the 6-in. strip is affixed by masking tape, extending $^1/_4$ in. over the sides, to a stand or easel at 50 deg from the horizontal. Since two separate flowdowns are made on each such specimen plate, $^1/_4$-in. tape may be applied vertically to the center of the panel as a separator. One fluid ounce of the lacquer under test is brought to 25 ±1 deg C and flowed down over the 2 × 7-in. area, pouring as closely as possible to the top edge and completing the pour in four rapid passes across the 2-in. space. If the surplus is recovered as it flows from the lower edge, it will be found that about 24 ml will be recovered, requiring a consumption of about 6 ml or $^1/_5$ fluid oz (approximately) for the test film.

Consideration or control of viscosity or nonvolatile content of the materials under test is not made at the time of coating these specimens. Since most furniture-type lacquers are supplied ready for use, it is presumed that the material under test is of viscosity and solid content amenable to normal spray application. Experimentation therefore has been based upon lacquers ranging naturally from 21 per cent to 30 per cent nonvolatile, and in viscosity from 45 sec to 70 sec, ASTM No. 7 Cup, as a representative coverage for clear cellulosic materials at spraying consistency. Since distention is made of each pour at three stations for an average result, the thickness of film deposited at the respective stations has been observed and considered carefully. Station A is at $1^1/_2$ in. from the top of the pour, Station B at $3^1/_2$ in., and Station C at $5^1/_2$ in., respectively.

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[3] "Brittle Lacquer Stress Analyzers," by C. W. Smith, *Paint Incorporating Paint Manufacture*, vol. 17, October, 1947, pp. 333–335.

[4] "Improvements Derived From Using Resins Designed Specifically for Lacquers," by J. O. Small, *Official Digest*, Federation of Paint and Varnish Production Clubs, no. 288, January, 1949, pp. 23–35.

Film thickness of the pour, for lacquers at spraying consistency, will be found to range from 0.0005 to 0.0007 in. at Station A, according to viscosity and nonvolatile content and to increase about 0.0002 in. at each subsequent station. Such is the secondary influence of the viscosity and nonvolatile factors that their influence on film thickness may be ignored in the process of achieving a distention-potential value of cellulosic materials at spraying consistency.

Application of the distorting pressure is made in a modification of the familiar Mullen tester used for paper testing, and which is modified to a distention apparatus by the addition of a 0.0001-in. dial gage, mounted with the plunger contacting the center of the operating area for the purpose of measuring the spherical radius of the distention.[5]

### CURING THE FILM

The cure of films for the significant evaluation of distention potential must be constant for a dual purpose: to bring the films to a constant condition as pertains to solvent content, and to insure a consistent condition of moisture in the film. It has been found that films of this thickness on a copper substrate may be brought to a very satisfactory constant condition by curing for 16 hr at 120 F in a forced-draft convection oven. This forcing period may be applied at any time after 15 min following application of the films, up to 8 hr.

### TEMPERATURE AT TIME OF TEST

Actual performance of the distention operation at room temperature was found to result in a certain instability and inaccuracy of result. While the actual degree of error prevailing is not significantly great, it is found that the numerical value of the distention factor obtained is approximately proportional in direct ratio to the temperature of the film and substrate at the moment of drawing, Fig. 1.

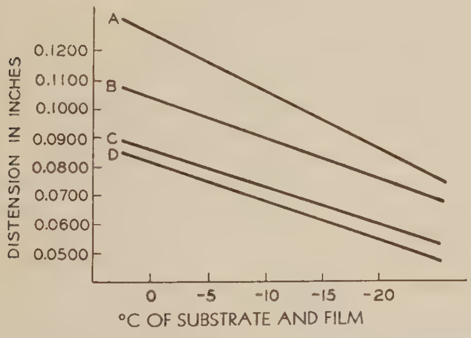

FIG. 1 EFFECT OF TEMPERATURE AT TIME OF DISTENSION ON FOUR REPRESENTATIVE LACQUER FILMS

The process of arriving at the correct temperature for testing, where a machine based on the Model C Mullen tester is cooled by placing it within a refrigerator, is shown in Fig. 2. It will be noted that the hydraulic fluid of the machine will have reached a temperature of about —3 C (26.6 F) in 1 hour, a point generally satisfactory for making check evaluation distentions.

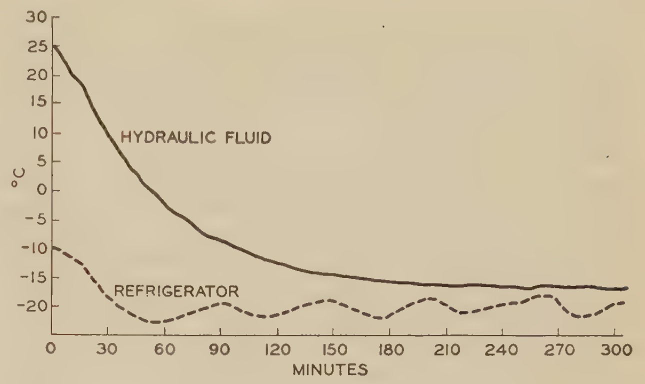

FIG. 2 PROGRESSIVE COOLING OF HYDRAULIC FLUID OF DISTENTION MACHINE WHEN PLACED IN A REFRIGERATOR AT —20 C

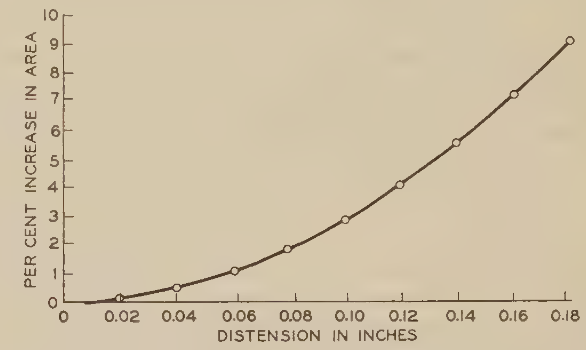

FIG. 3 RATIO OF DISTENTION OF FILM IN 0.0001 IN. ON RADIUS OF SPHERICAL DISTENTION TO ACTUAL INCREASE IN AREA IN PER CENT

### PERFORMANCE OF TEST

Specimens are removed directly from the oven for placement in the distention machine for testing. Reduced as the films are by the 16 hr of elevated temperature curing to a minimum constant as pertains to moisture content, the film will absorb atmospheric moisture rapidly after removal from the oven. Since the checking potential of many films is affected by moisture content, it is important that this factor be maintained constant.

Under a concentrated light, such as from a microscope illuminator, directed obliquely on the exposed circular area within the clamp of the machine, the incidence of failure of the film by abrupt fracture is positive and instantaneous and readily observed. The possible variation of rate of application of pressure is not great, though turning of the compressing screw at a constant speed is advisable. The motor-driven machine operates at 120 rpm. On observation of fracture failure, the pressure increment is stopped at once, and the vertical distention at the center of the spherical distortion is read to 0.0001 in. accuracy. Expression of the distention-potential factor in per cent of expansion of the area involved is plotted in Fig. 3. The per cent increase of the circular area distended into a spherical segment is calculated by the formula

$$P = \frac{100D^2}{R^2}$$

where

$D$ = vertical distention as read from dial gage of distention machine

$R$ = radius of distended area, or 0.59375 in.

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[5] U. S. Patent no. 2,332,818.

Stations A, B, and C, representing progressive distances from the top of the flowdown as previously described, are run successively, and the results in 0.0001 in. are averaged for the expressed value for the material under test.

### Influence of Film Thickness on Checking Tendency

While it has been customary to assume in both tests and practice that, all else being equal, checking hazard increases more or less in proportion to film thickness, viz., that a heavy film is immediately more conducive to checking failure, experience in reading distention potentials and, ergo, the tendency of the film to exhibit failure by checking, serves to indicate that this ratio is not a true proportionate one. Koenig[2] indicates that the rate and extent of the development of stresses in a cellulosic film drying by evaporation of solvent, is influenced not only by the thickness of the film, but by the rate of evaporation, viz., the nature of the solvents and the ambient condition of the atmosphere, the solvent-retention properties of the nonvolatile constituents, and the aging factor of the stress development. While it cannot be denied that film thickness is a factor in checking propensity, the number of variables present is such that prognostications of proportionate influence cannot be made with impunity.

Examinations made of films ranging from 0.0005 in. to 0.0050 in. thickness by the distention-potential method show relatively little proportionate effect due to the fact that a standard procedure of curing the films for test will not develop in all thicknesses of film the same degree of stress. The greater mass of the heaviest films is prevented from early failure by the presence of unreleased solvent and the incomplete development of stresses. The very fact that the release of solvent is more gradual, in itself, affects the final extent, direction, and nature of the end stresses developed. The exact extent and behavior of the end stresses developed in any one application and of any one formulation of film-forming material defying comprehensive regimentation, it does not seem possible to formulate a rule for the exact effect of film thickness on checking tendency.

The normal effect of film thickness on the distension-potential test for one representative low-potential material is shown in Fig. 4. An increase here of slightly over 100 per cent in film thickness—from 0.0007 in. to 0.0015 in.—serves to reduce the distention potential about 200 points, causing its classification to descend from Class III into Class IV. The actual differential represented would probably amount to from 3 to 5 cycles of panel checking value. This material is a sealer, and since the curve enters Class IV at a film thickness of slightly over 0.0010 in., it is considered a Class III material with a normal checking potential of 8 to 10 cycles.

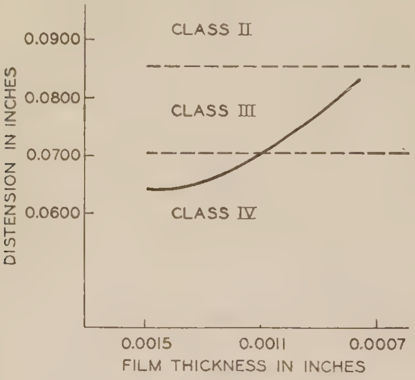

Fig. 4 Effect of 100 Per Cent Increase of Thickness of Test Film of Conventional Class III Lacquer

Film thickness of ready-to-spray lacquers may be disregarded in this test since the film deposited by the temperature and angle of incident flowdown is in itself a characteristic of the individual material. The natural flow and "hang" of the material, as affected by viscosity, rate of solvent release, and nonvolatile content, will induce a similar corresponding effect in commercial application. Thus a material which, as offered at spraying consistency, deposits a film of certain thickness having a distention potential of a specific value for this normally deposited film of the material, may be assigned a significant evaluation of its potential behavior in commercial use.

Commercial application of course connotes a heavier film than is used in the laboratory distention evaluation. It is possible, however, by correlation of these results with field experience to assign a relative value to the behavior of uniformly cured films which is an equitably accurate criterion of their ultimate behavior in field use.

### Interpretation and Correlation of Results

Values in checking potential which are assigned, therefore, through the Class I to Class IV evaluation just described, are so adjusted as to connote a prediction of the behavior of the material in question in conventional practice.

All coating materials are evaluated singly whether designed and used as an undercoat or as a finishing coat. Such materials are usually formulated for reciprocal association and, as such, will be found to fall into a similar bracket of distention potential. In this case the resulting distention value is considered the value for the complete system, consisting usually of an undercoating and two finishing coats.

Where a wide divergence of value between under and finishing elements is obtained, it is indicated that the finishing coat is the dominant factor in checking. Not only is a greater amount of this material applied in the double coat in conventional use, but by being superimposed in the system and exposed to the air, earlier development of complete stress is realized. If the undercoat exhibits a lower distention potential, its effect will be much delayed by the slower development of stresses due to its submergence in the system. Further, the undercoat, lying adjacent to the insulating substrate formed by wood, is never subjected to as abrupt thermal shock as is the surface coating.

Adequately accurate predictions of the potential checking resistance of furniture-type finishing systems may be made by assigning a value to the system, based upon the proportionate application of the respective materials in question. Thus if an undercoat and finishing coat fall into the same distention potential class, that value may be accepted as the value for the system. Unless the distention potential of the undercoat is two or more classes below that of the finishing coat, the value of the finishing coat may be accepted for the entire system in practically all cases. Where the differential between materials is several classes, the aggregate point for the system will fall a point between the extremes proportionate to the number of applications of each respective material. For example, in case of a wide divergence in undercoat and top coat to be used as a single and double coat, respectively, the potential checking-point value will be approximately one third of the differential between the individual values below the greater.

It may be that the underlying causes of cold checking, especially as pertain to basic formulation characteristics, have not been understood completely. Sanding sealers, for example, are generally considered to be "short" materials as a concession to their incorporated sanding property. The issue, however, is confused in a measure by the fact that not all the factors conducive to production of a "short film," are contributors to early cold-checking tendency. The use, for example, of metallic soaps as sanding agents does not contribute largely to checking tendency, nor does the amount of added plasticizing agent or the rate of solvent release. The principal offender in cold-check failure is the hard resin. Softness or "cheesiness" of a sealer film, or even some degree of brittleness, as evinced by some such test as a mandrel bend, do not necessarily connote low cold-check resistance. Decrease or omission of plasticizer in a typical furniture-lacquer formulation will be reflected in the distention potential, and in a manner which reveals that the effect of plasticity so induced is not proportionate but takes the form of a logarithmic curve.

In Fig. 5, material (A), a high-grade piano lacquer, falls from its normal position as a Class I material at a distention factor of 0.1153 to Class III, distention factor 0.0833 with the omission of 25 per cent of the normal plasticizer. It remains thereafter in Class III even when plasticizer is omitted completely. Material (B), a conventional furniture rubbing lacquer, has, as shown, a normal distention potential of approximately 0.0800. Elimination of 37.5 per cent of the plasticizer causes the rating to fall into Class IV, where it remains throughout the progressive elimination of the remainder of the plasticizer. The addition of extra plasticizer, to the extent of overplasticizing the material by 20 per cent, serves to raise the distention potential of the material into Class I at sacrifice of course of other such essential properties as resistance to printing and shrinkage.

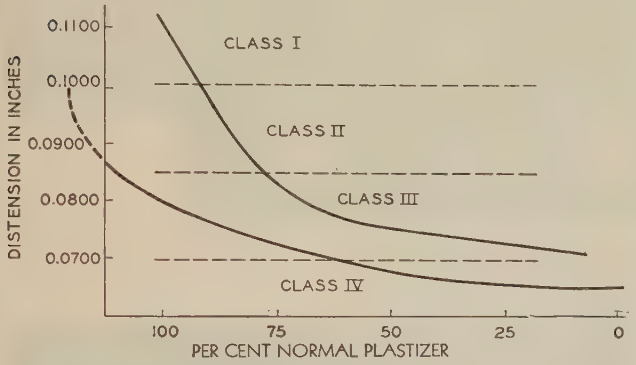

FIG. 5 EFFECT OF PLASTICIZER CONTENT ON DISTENTION OF A HIGH-POTENTIAL PIANO LACQUER (UPPER CURVE) AND A CLASS II RADIO-CABINET MATERIAL

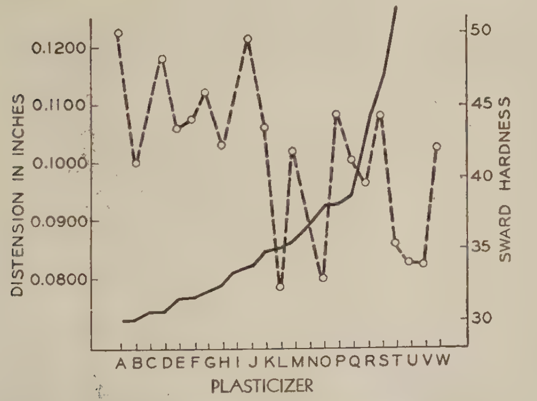

FIG. 6 LACK OF RELATIONSHIP BETWEEN DISTENTION POTENTIAL (SOLID LINE) AND SWARD HARDNESS (BROKEN LINE) OF CELLULOSIC SOLUTION WITH 23 DIFFERENT PLASTICIZERS

Significant development of high distention potential does not occur until the maximum permissible plasticity (as gaged by other pertinent factors) is approached or exceeded. Varying amounts of plasticizer will not affect the distention potential of a film in the same ratio as they will a mandrel bend or similar flexing or bend test.

That distensibility is a distinct property of the film is shown clearly in Fig. 6. Here a standard cellulose-resin solution was treated with 23 different plasticizers. Distentions were made, and the results plotted in ascending order. Sward hardnesses of the films drawn on plate glass by doctor blade are plotted in superimposed position over the distentions. The obvious absence of relationship in these properties needs no comment.

Fig. 7 shows equipment for distention of test sheets. Fig. 8 shows a typical test plate. Two pours, or flowdowns are shown, each with its respective three test stations. This is a lacquer of very high distention potential showing no failure here with all stations drawn to approximately 0.1840 in. in a vertical direction.

Fig. 9 shows a typical failure in a high-grade piano lacquer. The film thickness here is 0.0011 in., and the recorded distention potential, 0.1080, making this a Class I material which might be expected to resist efforts to check it on wood panels for an almost infinite number of cycles.

Fig. 10 shows the same piano lacquer having the distention test run on a heavy film of 0.0023 in. thickness. The "veined leaf" pattern is typical of the failure obtained from a thick film of high-potential material. The distention potential obtained here is 0.0963, showing that the excessive film causes a recession of value to the extent of one class only.

Figs. 11 and 12 are typical extreme fractures obtained from very brittle materials of low checking potential. The concentric fracture and glasslike shattering are typical. Fig. 11 is a clear furniture lacquer showing a distention potential of 0.0648. This is a Class IV material which would not be expected to exceed 3 cycles of panel testing. Fig. 12 of the same basic formula is a low-potential batch failing at 0.0567. Note the glasslike shattering combined with concentric fracture rings.

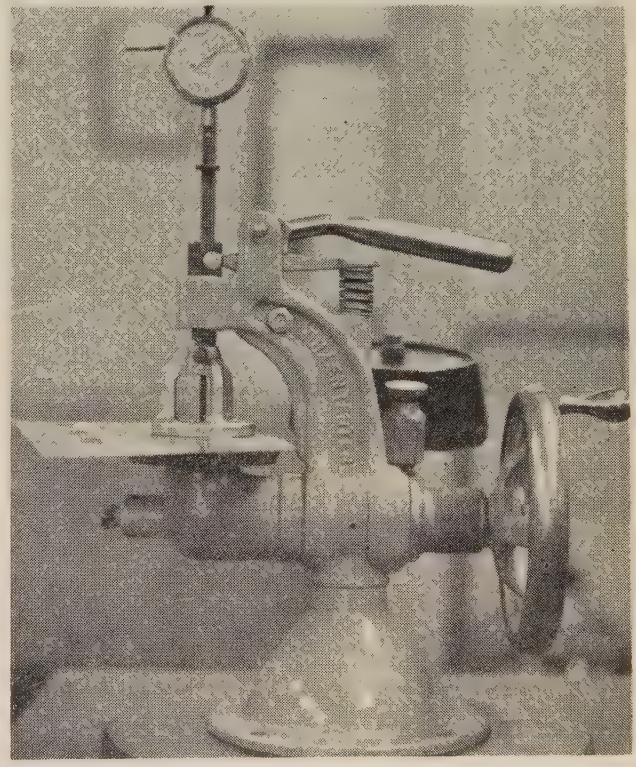

FIG. 7 EQUIPMENT FOR THE HYDRAULIC DISTENTION OF TEST SHEETS (U. S. Patent 2,332,818.)

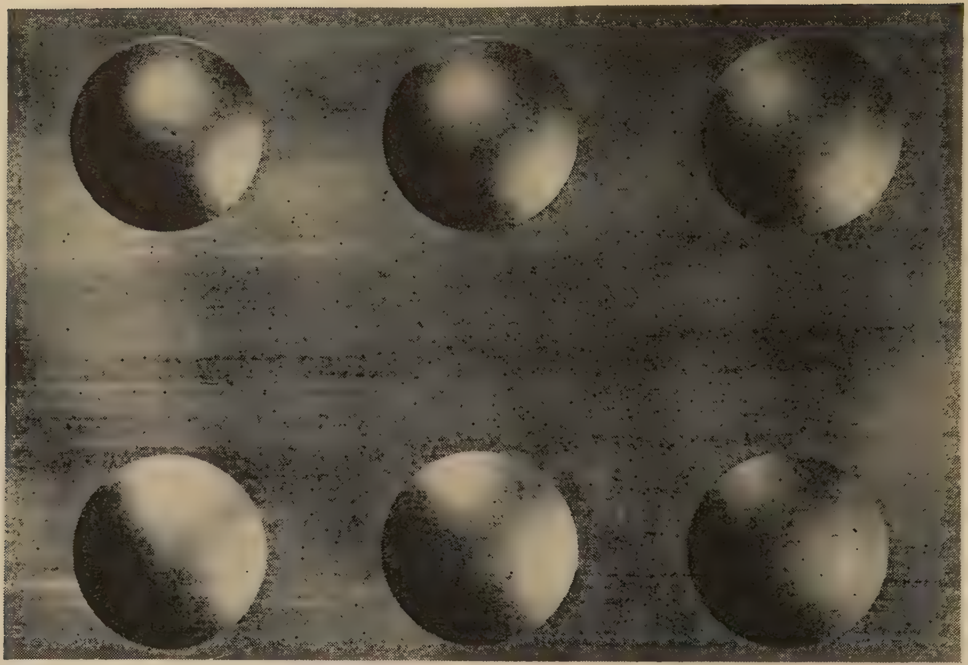

Fig. 8 Test Plate Showing Two Flowed Specimens and Three Test Stations on Each

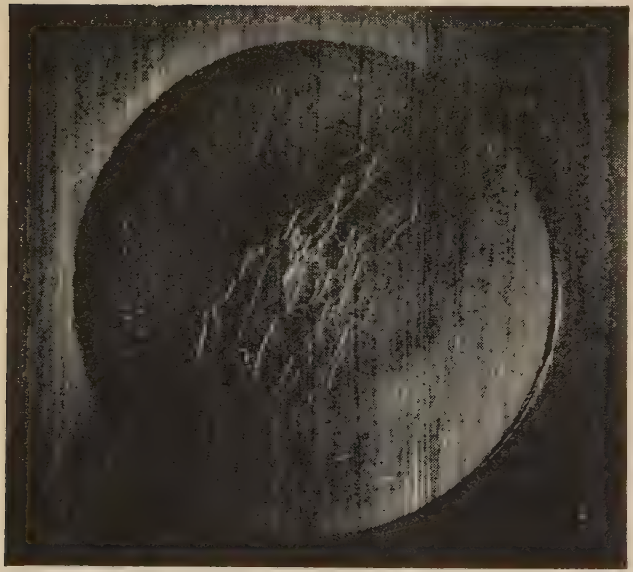

Fig. 9 Typical Failure of a High-Potential Piano Lacquer

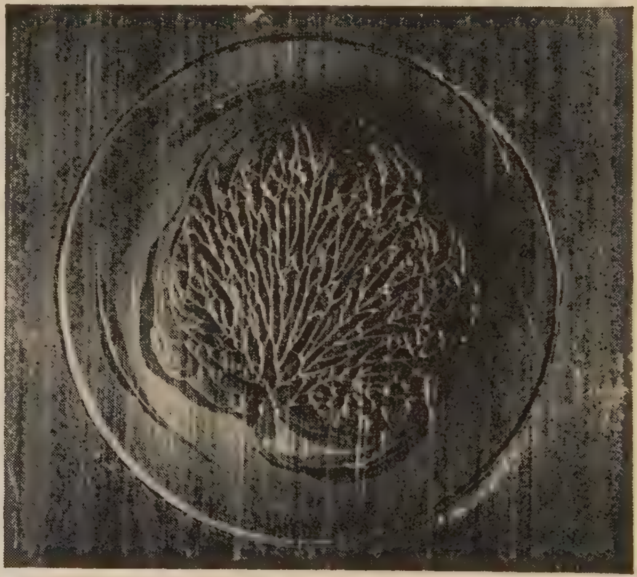

Fig. 10 "Leaf" Pattern Failure of a Heavy (0.0023-In.) Film of Piano Lacquer Shown in Fig. 9

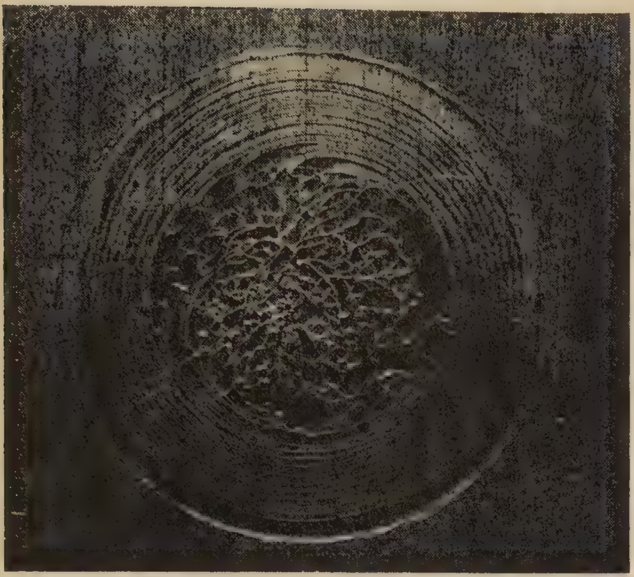

FIG. 11 FAILURE OF A LOW-POTENTIAL BRITTLE LACQUER SHOWING TYPICAL CONCENTRIC FRACTURE

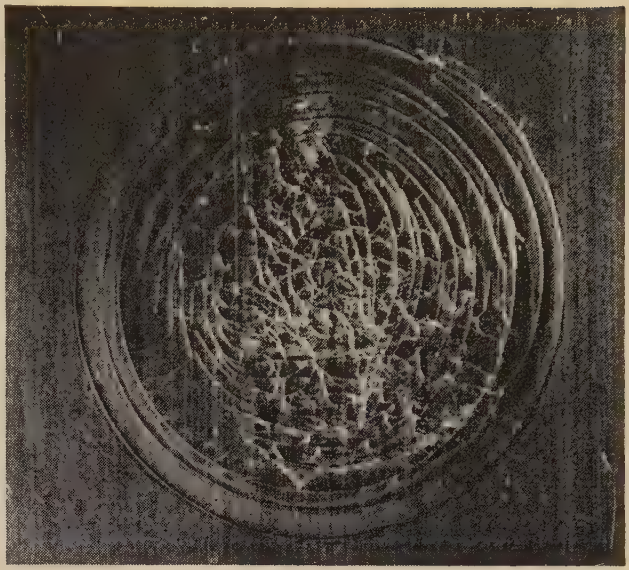

FIG. 12 FAILURE OF A VERY BRITTLE LOW-POTENTIAL LACQUER (Concentric fracture supplemented by glasslike shattering.)

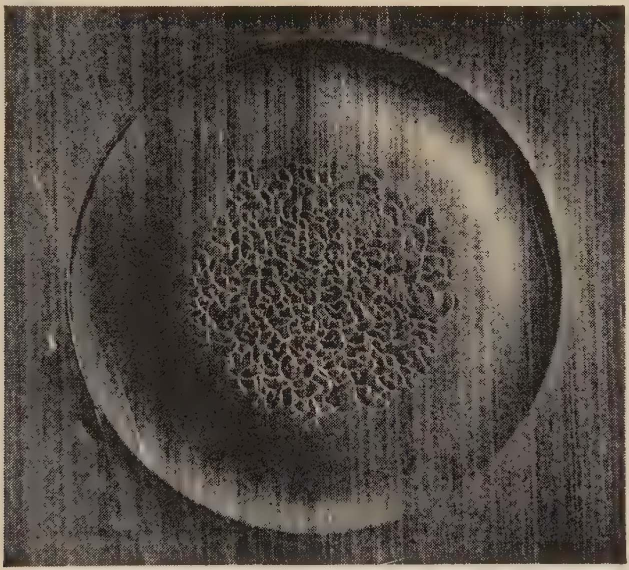

FIG. 13 TYPICAL "ALLIGATOR" PATTERN FAILURE OF A SOFT FLEXIBLE FILM OF HIGH DISTENTION POTENTIAL

Fig. 13 illustrates the characteristic uniform small-pattern check of a soft "cheesy" film material. Here, as in the other illustrations, the fracture pattern itself is not a criterion of check-resistance potential, but the failure, when reached, will take these general forms in accordance with respective film types. The material shown in Fig. 13 is a sanding sealer. It is a high-check-resistant material having a distention of 0.0924 or Class II, and connoting a panel-test resistance of 15 to 18 cycles.

# Effect of Fuel-Immersion on Laminated Plastics

By W. A. CROUSE,[1] MARGIE CARICKHOFF,[2] and MARGARET A. FISHER[2]

**The effects of cyclic and of continuous immersion in heptane, toluene, and SR-6, a test fuel, on the weight, dimensions, and flexural properties of nineteen samples of laminated plastics are reported. No one sample exhibited smaller changes than all other samples in all properties for all fuels, and for both cyclic and continuous immersion. The best weight and dimensional stability in the cyclic test was shown by a glass-fabric unsaturated-polyester laminate. The changes in flexural strength as well as in modulus of elasticity were losses in the majority of cases after the cyclic- and the continuous-immersion test. The unsaturated-polyester laminates varied widely among themselves in regard to the magnitude of the changes in a given property after an immersion test.**

## INTRODUCTION

INFORMATION regarding the effects of immersion in various fuels on the properties of laminated plastics is needed to evaluate these materials for use on aircraft, and to prepare specifications for such materials as are found suitable for this purpose.

This paper presents the results of tests made to determine the effects of cyclic and continuous immersion in three fuels on the weight, dimensions, and flexural properties of nineteen representative laminated plastic materials. The cyclic-immersion test involved alternate 24-hr periods of fuel-immersion and air-drying. The continuous-immersion test involved immersion in the fuels for different periods of time between 7 and 360 days. Both types of test were carried out at only one temperature, 77 F.

In view of the variability in properties to which the materials herein examined are usually subject, no attempt has been made to draw general inferences regarding the superiority of one or more of these materials relative to the others.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

## MATERIALS AND FUELS

The materials used in this investigation included commercial grades such as Grade C, L, and AA phenolic laminates, and several experimental materials of interest for aircraft application. The experimental samples were as follows: A number of unsaturated-polyester resin laminates reinforced with glass and cotton fabrics, a cotton-fabric melamine-resin laminate, a high-strength-paper phenolic laminate, a rayon-fabric phenolic laminate, two experimental phenolic laminates made with high pressure and low pressure, respectively, using the same Grade C cotton fabric as filler, and a paper-base lignin laminate.

The materials are described in detail in Table 1. They were obtained in the form of sheets approximately $^1/_8$ in. thick.

The fuels used were heptane (an aliphatic hydrocarbon), toluene (an aromatic hydrocarbon), and SR-6, a representative aircraft test fuel (a blend of aliphatic and aromatic hydrocarbons). The heptane used was a commercial *n*-heptane and the toluene, a technical toluene, both supplied by the Phillips Petroleum Company. The SR-6 used was a mixture of di-isobutylene (60 per cent), toluene (20 per cent), xylene (15 per cent), and benzene (5 per cent), and 0.2 lb of aviation-gasoline inhibitor per 1000 gal, supplied by the Standard Oil Company of New Jersey. The inhibitor consists of 50 per cent of *n*-butyl-*p*-aminophenol, 30 per cent of isopropyl alcohol, and 20 per cent of anhydrous methanol, and is added in order to hinder the oxidation of the di-isobutylene, a diolefin, with consequent gum formation.

## TEST PROCEDURES

*Specimens.* The dimensions of the test specimens were 1 in. × 3 in. × the thickness of the sheet. The specimens were machined on a surface grinder with tap water as a coolant. The length and width were kept to within ±0.005 in. of the given dimensions. One surface of each sheet was arbitrarily designated as the reference surface. The specimens of the cloth laminates were cut so that the direction with the greater number of threads per inch in the reference surface was lengthwise. As all the paper laminates were crossed-ply materials, the lengthwise direction of these specimens was arbitrarily taken parallel to one edge. The weight of the specimens varied from approximately 7 to 12 grams.

The specimens which were to be immersed were conditioned for 48 hr at 77 F and 50 per cent relative humidity (RH) prior to starting the tests.

*Weight and Dimensions.* The weight was determined to the nearest milligram. The length was measured to the nearest 0.001 in., and the width and thickness to the nearest 0.0001 in. The length was measured at two places, and the width and thickness at three places. The changes in weight and dimensions were determined with two specimens of each material. The changes in the length and width columns presented in the tables were determined by taking the mean of the average length changes and the average width changes.

*Flexural Properties.* The flexural tests were made in accordance with method No. 1031 of Federal Specification L-P-406a,[3] using the 1200-lb scale of the 2400-lb-capacity hydraulic testing machine shown in Fig. 1. The flexural apparatus, Fig. 2, has been described.[4] Load-deflection graphs were obtained in each test on a Southwark-Templin autographic recorder, which was operated by a Southwark-Peters plastics extensometer.

The 1 × 3-in. specimens, which were immersed in the various test fuels, were cut into two 1 × 1.5-in. specimens for the

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 49—F-32.

[3] Federation Specification L-P-406a: Plastics, Organic; General Specifications, Test Methods; Government Printing Office, Washington, D. C., January 24, 1944.

[4] "A Variable Span Flexure Test Jig for Plastic Specimens," by B. M. Axilrod, R. W. Thiebeau, and G. E. Brenner, ASTM Bulletin no. 148, October, 1947, p. 96.

TABLE 1 DESCRIPTION OF MATERIALS

| NBS Designation | Type of Laminate | Manufacturer | Thickness[a] (in.) | Density[a] (g/cm$^3$) | Resin | | Reinforcement | | | Ply Arrangement | No. of Plies | Pressure (lb/in$^2$) | Molding Conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | Curing Temperature | | Time | |
| | | | | | Designation | Content, by Weight (%) | Type | Thread Count Warp | Thread Count Filling | | | | Initial (°F) | Maximum (°F) | Curing (min.) | Cooling (min.) |
| C | High-Strength-Paper Phenolic | Consolidated Water Power and Paper Co | 0.121 | 1.42 | -- | -- | Paper | -- | -- | Crossed | | 250 | | | | |
| D | Lignin Paper | Formica Insulation Co. | 0.128 | 1.38 | Lignin | | Lignin Paper | | | | | | | | | |
| E | Glass-Fabric Unsaturated Polyester | Swedlow Aeroplastics Corp. | 0.134 | 1.69 | Marco MR-1A | 55-63 | Glass Fabric, plain weave | 29 | 17 | Crossed | 7 | | | | | |
| F | Muslin-Cotton-Fabric Unsaturated Polyester | Swedlow Aeroplastics Corp. | 0.123 | 1.31 | Marco MR-1A | | Cotton Fabric (Muslin), twill weave | 70 | 48 | | 7 | | | | | |
| H | Enameled-Duck Cotton-Fabric Unsaturated Polyester | Pittsburgh Plate Glass Co., Columbia Chemical Division | 0.147 | 1.36 | Allymer CR 39 | 62-65 | Cotton Fabric (Enameled Duck), plain weave, 8 oz/yd$^2$ | 36 | 32 | Crossed | 6 | 1-5 | 158 | 239 | 2 hr at 158°F,<br>10 hr at 158-239°F. | Gradual |
| I | Grade C Phenolic | Synthane Corp. | 0.124 | 1.35 | Bakelite BV-1112 | 48 | Cotton Fabric, plain weave, 10 oz/yd$^2$ | 50 | 40 | Crossed | 7 | 1800 | | 340 | 50 | 20 |
| J | Grade L Phenolic | Synthane Corp. | 0.124 | 1.34 | Bakelite BV-1112 | 48-52 | Cotton Fabric, plain weave, 3.7 oz/yd$^2$ | 80 | 80 | Parallel | 19 | 1620 | | 320 | 45 | 25 |
| K | Grade AA Phenolic | Synthane Corp. | 0.145 | 1.49 | Bakelite No. 2427 | 47 | Asbestos Fabric, plain weave, 18 oz/yd$^2$ | 18 | 16 | Parallel | 5 | 1800 | | 340 | 50 | 20 |
| L | Enameled-Duck Cotton-Fabric Phenolic | Bakelite Corp. | 0.152 | 1.36 | Bakelite BV-16887 | 52 | Cotton Fabric (Enameled Duck), plain weave, 8 oz/yd$^2$ | 84 | 28 | Crossed | 9 | 250 | | 325 | 30 | |
| M | Canvas-Cotton-Fabric Melamine | Formica Insulation Co. | 0.145 | 1.47 | | 50-55 | Cotton Fabric (Canvas), plain weave, 8 oz/yd$^2$ | 90 | 28 | Parallel | 11 | 1400 | | 284-288 | | |
| N | Canvas-Cotton-Fabric Unsaturated Polyester | Formica Insulation Co. | 0.150 | 1.13 | Laminac | 50-55 | Cotton Fabric (Canvas), plain weave, 8 oz/yd$^2$ | 90 | 28 | Parallel | 7 | 15 | | 230-248 | | |
| S | High-Strength-Paper Phenolic | Consolidated Water Power and Paper Co. | 0.122 | 1.42 | Bakelite No. 16526 | 30 | High Strength Mitscherlich Paper | -- | -- | Crossed | 54 | 250 | | 310±10 | 12 | Gradual |
| V | Low-Pressure Grade C Phenolic | Synthane Corp. | 0.150 | 1.26 | Bakelite BV-16887 | 51 | Cotton Fabric (Army Duck), plain weave, 10 oz/yd$^2$ | 50 | 40 | Crossed | 7 | 180 | | 320 | 50 | |
| W | High-Pressure Grade C Phenolic | Synthane Corp. | 0.138 | 1.36 | Bakelite BV-1112 | 47 | Cotton Fabric (Army Duck), plain weave, 10 oz/yd$^2$ | 50 | 40 | Crossed | 7 | 1800 | | 320 | 50 | |
| X | Glass-Fabric Unsaturated Polyester | Pittsburgh Plate Glass Co., Columbia Chemical Division | 0.125 | 1.64 | Allymer CR 149 | 50-55 | Glass Fabric (ECC-11-162), plain weave, 12 oz/yd$^2$ | 28 | 16 | Crossed | 6 | 1-5 | 176 | 207 | 18 hr at 176°F.<br>1 hr at 207°F. | Gradual |
| Y | Glass-Fabric Unsaturated Polyester | Pittsburgh Plate Glass Co., Columbia Chemical Division | 0.114 | 1.66 | Allymer CR 39 | 48-50 | Glass Fabric (ECC-11-162), plain weave, 12 oz/yd$^2$ | 28 | 16 | Crossed | 6 | 1-5 | 176 | 207 | 15 hr at 176°F.<br>1 hr at 207°F. | Gradual |
| Z | Rayon-Fabric Phenolic | Formica Insulation Co. | 0.160 | 1.35 | Iron-sides 91-L | 37-40 | Rayon Fabric (Celanese Corp., WE-3975), high tenacity Fortisan rayon warp thread, cotton filling thread, twill weave, 12.5 oz/yd$^2$ | 75 | 12 | Crossed | 6 | 1100 | | 320 | Temperature allowed to remain over 302°F for 20 min. | 20 |
| AA | Glass-Fabric Unsaturated Polyester | Marco Chemicals Inc. | 0.118 | 1.69 | Marco MR-17B | 45.5 | Glass Fabric (ECC-11-162), plain weave | 29 | 17 | Parallel | 7 | None | 140 | 240 | 1 hr at 140°F.<br>1 hr at 240°F. | |
| AB | Glass-Fabric Unsaturated Polyester | Army Air Forces, Air Technical Service Command | 0.130 | 1.84 | Plaskon 900 | 43 | Glass Fabric (ECC-112), Heat Treated, plain weave | 40 | 40 | Parallel | 45 | 40 | 180 | 220 | 2 hr at 180°F.<br>2 hr at 220°F. | |

a. Average for all specimens tested.

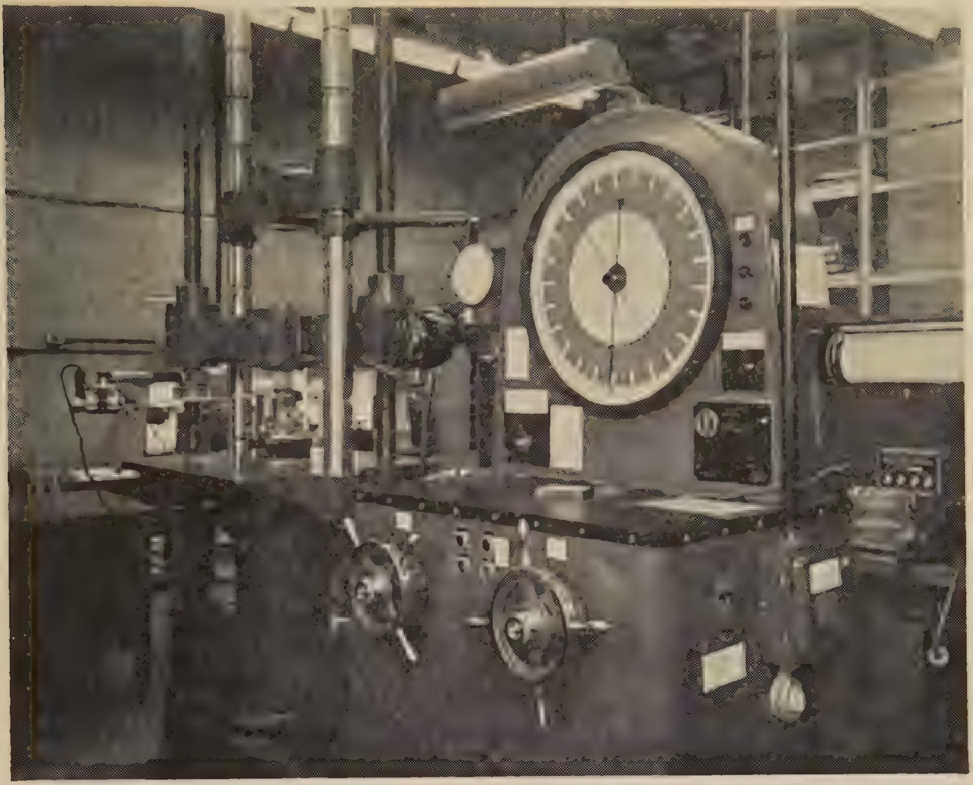

Fig. 1 Hydraulic Testing Machine

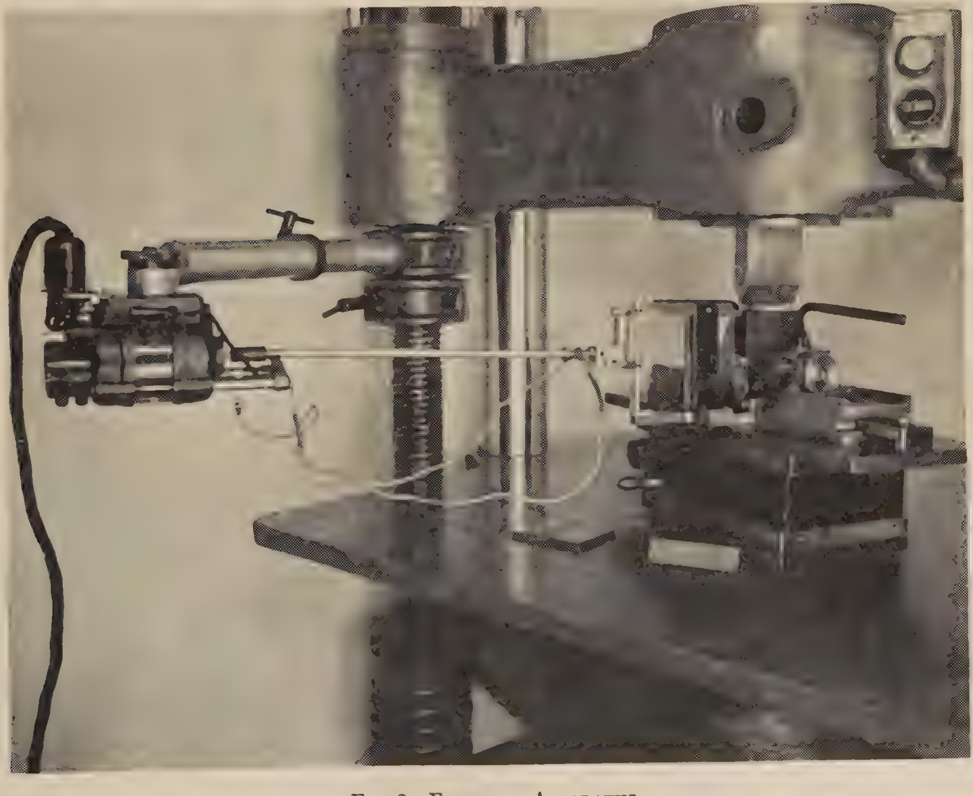

Fig. 2 Flexural Apparatus

flexural tests. Because the test specimens were too short, a span-depth ratio of 8:1 was used instead of 16:1, as prescribed by Federal Specification L-P-406a. The reference surface of the specimen was on the tension side during the test. The radius of the support and pressure pieces was $^1/_{32}$ in. The relative rate of head motion was 0.01 ipm.

The flexural strength and the flexural modulus of elasticity were calculated in accordance with the equations given in method No. 1031 of Federal Specification L-P-406a. The flexural-strength values reported are considered to be accurate to 1 per cent, and the flexural modulus of elasticity values to 3 per cent. All the values for the flexural properties are the averages obtained with four specimens except the initial values, which are the averages for six specimens.

The initial values for the flexural properties were determined on specimens which were heated in a circulating-air oven at 122 F for 48 hr and then conditioned for 48 hr at 77 F and 50 per cent RH prior to test. The changes in the flexural strength and the flexural modulus of elasticity as a result of immersion in the various fuels were calculated from these initial values.

*Cyclic and Continuous Fuel-Immersion Tests.* Each cycle of the cyclic fuel-immersion test consists of a 24-hr immersion and a 24-hr drying period. The specimens were immersed individually in 200 ml of test fuel in closed glass containers. Weight and dimensional measurements and flexural tests were made after 10 cycles of test and reconditioning at 77 F and 50 per cent RH for 48 hr.

The continuous fuel-immersion test consists of 7, 30, 90, 180, and 360 days of immersion. The specimens were immersed individually in 200 ml of test fuel in closed glass containers. Weight and dimensional measurements and flexural tests were made immediately after removing the specimens from the fuel on one set of specimens, and after reconditioning for 7 days at 77 F and 50 per cent RH on a second set.

TABLE 2 CHANGES IN WEIGHT AND DIMENSIONS OF LAMINATED PLASTICS AFTER THE CYCLIC FUEL-IMMERSION TEST[a]

| NBS Material Designation | Change[b] in Weight in: | | | Average[b] of Length and Width Changes in: | | | Change[b] in Thickness in: | | |
|---|---|---|---|---|---|---|---|---|---|
| | Heptane (%) | Toluene (%) | SR-6 (%) | Heptane (%) | Toluene (%) | SR-6 (%) | Heptane (%) | Toluene (%) | SR-6 (%) |
| Lignin paper | | | | | | | | | |
| D | 0.08 | 0.52 | 0.06 | 0.02 | 0.05 | 0.00 | 0.3 | 0.2 | -0.1 |
| Phenolic; high-strength paper | | | | | | | | | |
| C | 0.09 | 0.42 | 0.01 | 0.00 | 0.01 | -0.01 | 0.1 | 0.0 | -0.1 |
| S | 0.10 | 0.35 | 0.04 | 0.02 | 0.04 | -0.04 | 0.2 | 0.2 | 0.1 |
| Phenolic; cotton fabric | | | | | | | | | |
| J (Grade L) | 0.07 | 0.42 | 0.01 | 0.02 | 0.05 | -0.01 | -0.1 | 0.1 | -0.1 |
| I (Grade C) | 0.10 | 0.56 | 0.02 | 0.01 | 0.05 | -0.02 | 0.2 | 0.0 | -0.8 |
| W (Grade C) | 0.14 | 0.85 | 0.05 | 0.04 | 0.07 | 0.02 | 0.1 | 0.0 | -0.3 |
| L (Grade C; low pressure) | 0.26 | 0.88 | 0.14 | 0.03 | 0.09 | -0.03 | 0.5 | 0.1 | 1.6 |
| Phenolic; rayon fabric | | | | | | | | | |
| Z | 0.34 | 0.33 | 0.32 | 0.04 | 0.05 | 0.04 | 0.0 | 0.2 | 0.0 |
| Phenolic; asbestos fabric | | | | | | | | | |
| K | 0.16 | 0.83 | 0.20 | 0.02 | 0.05 | 0.03 | 0.0 | 0.2 | 0.5 |
| Melamine; cotton fabric | | | | | | | | | |
| M | 0.16 | 0.65 | -0.03 | 0.03 | 0.08 | -0.03 | 0.1 | 0.4 | -0.2 |
| Unsaturated polyester; cotton fabric | | | | | | | | | |
| F | 0.09 | 0.54 | 0.00 | 0.02 | 0.08 | -0.03 | 0.0 | 0.3 | -0.4 |
| H | 0.19 | 0.60 | 0.04 | 0.04 | 0.09 | 0.01 | 0.1 | 0.2 | -0.1 |
| N | 0.49 | 2.83 | 1.54 | 0.11 | 0.14 | 0.16 | 0.4 | 2.3 | 1.2 |
| Unsaturated polyester; glass fabric | | | | | | | | | |
| E | 0.09 | 0.30 | 0.14 | 0.00 | -0.02 | 0.00 | 0.0 | 0.5 | -0.4 |
| X | 0.08 | 0.08 | 0.08 | 0.01 | 0.01 | 0.01 | 0.0 | -0.1 | -0.1 |
| Y | 0.12 | 0.20 | 0.16 | 0.01 | 0.01 | 0.01 | 0.1 | 0.3 | -0.4 |
| AA | 0.00 | 0.29 | 0.06 | 0.00 | 0.00 | 0.01 | 0.7 | 0.6 | 0.2 |
| AB | 0.17 | 0.21 | 0.19 | 0.03 | 0.01 | 0.03 | 0.2 | 0.0 | 0.1 |

[a] Each cycle of the test consists of a 24-hour immersion and a 24-hour drying period. Weight and dimensional measurements were made after 10 cycles of testing and reconditioning at 77° F and 50 percent relative humidity for 48 hours.

[b] Based on average value for two specimens.

## Results and Discussion

*Weight and Dimensional Changes.* The changes in weight, length, width, and thickness of the laminates immersed in heptane, toluene, and SR-6 are shown in Table 2 for cyclic fuel immersion, and in Tables 3 to 5, and Figs. 3 to 5, inclusive, for continuous fuel immersion. The samples having changes greater than ±1 per cent for weight, ±0.1 per cent for length and width, and ±0.5 per cent for thickness in the cyclic fuel-immersion test and after 360 days of continuous fuel immersion are shown in Table 9. The data for the low-pressure Grade C phenolic laminate V were not included in the tables and in the discussion because of its great variability, but are shown in Figs. 3 to 5.

(*a*) *Cyclic Fuel-Immersion Test.* In the cyclic fuel-immersion test, practically all of the weight changes of the samples for all the fuels as well as the majority of the dimensional changes for heptane and toluene are positive. In SR-6 nearly one half of the changes in length and width, and over one half of the changes in thickness are negative. The positive changes indicate that there is some retention of liquid accompanied by a slight swelling. Considering the magnitude of the changes for each sample in the three fuels regardless of sign, in the majority of cases the greatest changes in weight, and length and width of the samples occurred in toluene, whereas in thickness, the greatest changes were fairly well distributed between toluene and SR-6. The greater positive changes obtained with toluene compared to heptane may be partly ascribed to the greater volatility of heptane.

None of the samples showed weight changes in heptane of over 0.5 per cent, and about one half of them exhibited changes of 0.1 per cent or less. In toluene, the cotton-fabric unsaturated-polyester laminate N showed a change of 2.83 per cent. The remainder of the laminates changed less than 1 per cent, and about one half of the samples showed changes of less than 0.5 per cent. In SR-6 the laminate N showed a change of 1.54 per cent. The remainder of the samples showed changes of less than 0.35 per cent, and nearly one half of the samples exhibited changes of 0.05 per cent or less. The glass-fabric unsaturated-polyester laminate X had the smallest average change for the three fuels, with individual values of less than 0.1 per cent.

The laminate N showed length and width changes of 0.11, 0.14, and 0.16 per cent in heptane, toluene, and SR-6, respectively. The remainder of the samples exhibited changes of less than 0.1 per cent.

The cotton-fabric unsaturated-polyester laminate N in toluene and SR-6, and the low-pressure Grade C phenolic L in SR-6, showed thickness changes of 2.3, 1.2, and 1.6 per cent, respectively. The remainder of the samples changed less than 1 per cent.

The laminate X exhibited the greatest stability and the laminate N the least.

(*b*) *Continuous Fuel-Immersion Test.* In the continuous-immersion test the majority of the changes in weight and dimensions were positive. The

TABLE 3 CHANGES IN WEIGHT OF LAMINATED PLASTICS AFTER CONTINUOUS IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND

| NBS Material Designation | When Tested[a] | Change[b] After Immersion in Heptane For: | | | | | Change[b] After Immersion in Toluene For: | | | | | Change[b] After Immersion in SR-6 For: | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) |
| Lignin paper | | | | | | | | | | | | | | | | |
| D | i | 0.12 | 0.24 | 0.05 | 0.58 | 0.10 | 0.28 | 0.29 | 0.06 | 0.66 | 0.02 | 0.11 | 0.16 | -0.16 | 0.68 | -0.10 |
| | r | 0.22 | 0.34 | 0.06 | 0.56 | 0.11 | 0.18 | 0.32 | -0.02 | 0.66 | 0.00 | 0.16 | 0.22 | -0.12 | 0.63 | -0.12 |
| Phenolic;high-strength paper | | | | | | | | | | | | | | | | |
| C | i | 0.07 | 0.20 | 0.12 | 0.52 | 0.30 | 0.05 | 0.24 | 0.08 | 1.18 | 0.22 | 0.05 | 0.14 | -0.04 | 0.63 | 0.06 |
| | r | 0.18 | 0.30 | 0.16 | 0.52 | 0.32 | 0.15 | 0.33 | 0.07 | 0.62 | 0.18 | 0.22 | 0.20 | -0.08 | 0.56 | 0.08 |
| B | i | 0.05 | 0.18 | 0.08 | 0.47 | 0.18 | 0.08 | 0.20 | 0.09 | 0.56 | 0.14 | 0.06 | 0.14 | -0.06 | 0.56 | 0.00 |
| | r | 0.16 | 0.25 | 0.08 | 0.46 | 0.80 | 0.14 | 0.27 | 0.04 | 0.55 | 0.20 | 0.14 | 0.19 | -0.04 | 0.54 | 0.06 |
| Phenolic:cotton fabric | | | | | | | | | | | | | | | | |
| J (Grade L) | i | 0.13 | 0.26 | 0.16 | 0.54 | 0.18 | 0.13 | 0.34 | 0.13 | 0.82 | 0.30 | 0.12 | 0.22 | -0.03 | 0.70 | 0.04 |
| | r | 0.16 | 0.31 | 0.07 | 0.45 | 0.12 | 0.15 | 0.30 | 0.06 | 0.66 | 0.18 | 0.16 | 0.21 | -0.07 | 0.57 | 0.04 |
| I (Grade C) | i | 0.78 | 0.83 | 0.14 | 0.86 | 0.28 | 0.27 | 0.66 | 0.14 | 1.14 | 0.33 | 0.15 | 0.45 | -0.06 | 1.76 | 0.08 |
| | r | 0.26 | 0.42 | 0.08 | 0.69 | 0.16 | 0.22 | 0.37 | 0.06 | 1.00 | 0.19 | 0.28 | 0.32 | -0.10 | 0.80 | 0.00 |
| W (Grade C) | i | 0.35 | 0.63 | 0.36 | 1.12 | 0.42 | 0.56 | 0.61 | 0.32 | 1.63 | 0.40 | 0.24 | 0.62 | 0.12 | 1.26 | 0.24 |
| | r | 0.37 | 0.46 | 0.08 | 0.80 | 0.11 | 0.36 | 0.53 | 0.10 | 0.92 | 0.18 | 0.29 | 0.38 | 0.05 | 0.94 | 0.04 |
| L (Grade C; low pressure) | i | 0.84 | 0.97 | 0.78 | 1.52 | 0.76 | 1.00 | 1.18 | 0.86 | 1.82 | 0.91 | 0.90 | 0.94 | 0.57 | 1.66 | 0.70 |
| | r | 0.28 | 0.38 | 0.25 | 0.68 | -0.04 | 0.28 | 0.40 | 0.02 | 1.48 | 0.12 | 0.32 | 0.26 | -0.09 | 0.71 | -0.04 |
| Phenolic:rayon fabric | | | | | | | | | | | | | | | | |
| Z | i | 0.19 | 0.33 | 0.26 | 0.72 | 0.43 | 0.24 | 0.40 | 0.25 | 1.02 | 0.54 | 0.23 | 0.26 | 0.10 | 0.46 | 0.53 |
| | r | 0.11 | 0.15 | -0.04 | 0.44 | 0.15 | 0.09 | 0.18 | -0.04 | 0.64 | 0.18 | 0.10 | 0.10 | -0.10 | 0.58 | 0.18 |
| Phenolic;asbestos fabric | | | | | | | | | | | | | | | | |
| K | i | 0.62 | 1.35 | 0.94 | 1.15 | 0.74 | 1.57 | 1.38 | 1.64 | 1.70 | 1.48 | 1.09 | 0.86 | 0.73 | 1.57 | 0.94 |
| | r | 0.18 | 0.24 | 0.06 | 0.45 | 0.17 | 0.24 | 0.52 | 0.41 | 1.28 | 0.96 | 0.22 | 0.27 | 0.12 | 0.62 | 0.56 |
| Melamine;cotton fabric | | | | | | | | | | | | | | | | |
| M | i | 0.34 | 0.55 | 0.28 | 0.82 | 0.35 | 0.56 | 0.66 | 0.42 | 1.04 | 0.58 | 0.45 | 0.51 | 0.36 | 1.12 | 0.98 |
| | r | 0.05 | 0.20 | -0.10 | 0.36 | 0.02 | 0.13 | 0.29 | 0.00 | 0.50 | 0.12 | 0.21 | 0.14 | 0.02 | 0.44 | -0.50 |
| Unsaturated polyester;cotton fabric | | | | | | | | | | | | | | | | |
| F | i | 0.09 | 0.24 | -0.04 | 0.48 | -0.23 | 0.66 | 1.32 | 1.14 | 1.19 | 4.35 | 0.12 | 0.18 | -0.08 | 0.71 | -0.03 |
| | r | 0.16 | 0.21 | -0.04 | 0.42 | 0.16 | 0.20 | 0.55 | 0.52 | 0.90 | 2.72 | 0.12 | 0.12 | -0.11 | 0.55 | -0.04 |
| H | i | 0.14 | 0.28 | 0.13 | 0.80 | 0.18 | 0.26 | 0.50 | 0.37 | 1.77 | 1.05 | 0.18 | 0.27 | 0.03 | 1.18 | 0.54 |
| | r | 0.20 | 0.26 | 0.04 | 0.60 | 0.08 | 0.30 | 0.44 | 0.38 | 1.38 | 0.74 | 0.16 | 0.24 | 0.00 | 0.93 | 0.36 |
| N | i | 1.85 | 4.06 | 4.28 | 5.24 | 6.60 | 7.01 | 9.48 | 10.82 | 14.46 | 14.22 | 4.34 | 6.55 | 8.26 | 8.84 | 9.32 |
| | r | 0.20 | 0.49 | 0.30 | 0.85 | 0.52 | 1.60 | 3.42 | 4.77 | 5.66 | 5.59 | 1.26 | 1.58 | 1.40 | 4.72 | 4.34 |
| Unsaturated polyester;glass fabric | | | | | | | | | | | | | | | | |
| E | i | 0.11 | 0.22 | 0.28 | 1.16 | 0.34 | 0.46 | 2.39 | 3.73 | 6.80 | 4.98 | 0.25 | 0.44 | 0.52 | 2.31 | 1.30 |
| | r | 0.06 | 0.12 | 0.12 | 0.20 | 0.21 | 0.36 | 1.00 | 1.62 | 2.24 | 1.70 | 0.12 | 0.20 | 0.30 | 0.63 | 0.79 |
| X | i | 0.06 | 0.08 | 0.07 | 0.16 | 0.11 | 0.09 | 0.12 | 0.08 | 0.24 | 0.11 | 0.04 | 0.08 | 0.02 | 0.20 | 0.10 |
| | r | 0.04 | 0.06 | 0.04 | 0.14 | 0.11 | 0.03 | 0.08 | 0.04 | 0.19 | 0.11 | 0.03 | 0.05 | 0.00 | 0.15 | 0.08 |
| Y | i | 0.17 | 0.38 | 0.18 | 0.32 | 0.22 | 0.32 | 0.54 | 0.77 | 1.44 | 1.24 | 0.23 | 0.32 | 0.32 | 0.54 | 0.51 |
| | r | 0.02 | 0.03 | -0.04 | 0.14 | -0.01 | 0.08 | 0.24 | 0.52 | 0.85 | 1.06 | 0.06 | 0.05 | 0.02 | 0.31 | 0.34 |
| AA | i | 1.20 | 1.95 | 0.35 | 1.96 | 1.44 | 1.26 | 2.80 | 3.21 | 4.30 | 3.56 | 0.95 | 1.18 | 1.86 | 2.92 | 1.65 |
| | r | -0.14 | -0.15 | -0.16 | -0.04 | -0.21 | 0.08 | 0.26 | 0.58 | 1.17 | 0.96 | -0.20 | -0.06 | -0.10 | 0.18 | 0.72 |
| AB | i | 0.13 | 0.22 | 0.26 | 0.52 | 0.60 | 0.18 | 0.28 | 0.34 | 0.59 | 0.78 | 0.12 | 0.22 | 0.26 | 0.50 | 0.16 |
| | r | 0.07 | 0.11 | 0.02 | 0.20 | 0.06 | 0.08 | 0.14 | 0.04 | 0.34 | 0.16 | 0.07 | 0.10 | 0.00 | 0.27 | 0.09 |

a. Code for this column:
i = Tested immediately.
r = Tested after reconditioning for 7 days at 77° F and 50 percent relative humidity.

b. Based on average value for two specimens.

TABLE 4 AVERAGE OF CHANGES IN LENGTH AND WIDTH OF LAMINATED PLASTICS AFTER CONTINUOUS IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND

| NBS Material Designation | When Tested[a] | Change[b] After Immersion in Heptane For: | | | | | Change[b] After Immersion in Toluene For: | | | | | Change[b] After Immersion in SR-6 For: | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) |
| Lignin paper | | | | | | | | | | | | | | | | |
| D | i | -0.03 | 0.04 | 0.01 | 0.11 | 0.03 | 0.01 | 0.03 | -0.01 | 0.08 | 0.04 | 0.01 | 0.01 | -0.01 | 0.09 | 0.01 |
| | r | 0.03 | 0.05 | 0.01 | 0.09 | 0.02 | 0.03 | 0.06 | -0.02 | 0.10 | 0.02 | 0.01 | 0.02 | 0.01 | 0.09 | -0.01 |
| Phenolic;high-strength paper | | | | | | | | | | | | | | | | |
| C | i | 0.00 | 0.01 | 0.01 | 0.06 | 0.03 | 0.01 | 0.00 | 0.00 | 0.05 | 0.02 | 0.01 | 0.02 | 0.01 | 0.05 | 0.01 |
| | r | 0.02 | 0.01 | 0.00 | 0.08 | 0.06 | 0.02 | 0.03 | 0.01 | 0.06 | 0.04 | 0.01 | 0.01 | -0.03 | 0.07 | 0.03 |
| S | i | 0.00 | -0.01 | 0.02 | 0.02 | 0.05 | 0.02 | 0.01 | 0.02 | 0.06 | 0.04 | 0.03 | 0.00 | 0.00 | 0.05 | 0.02 |
| | r | 0.00 | 0.01 | 0.01 | 0.06 | 0.03 | 0.02 | 0.01 | 0.02 | 0.05 | 0.00 | 0.01 | 0.00 | 0.02 | 0.04 | 0.02 |
| Phenolic;cotton fabric | | | | | | | | | | | | | | | | |
| J (Grade L) | i | -0.01 | 0.01 | 0.00 | 0.10 | 0.03 | 0.01 | 0.04 | 0.01 | 0.11 | 0.06 | 0.00 | -0.01 | -0.01 | 0.07 | 0.03 |
| | r | 0.02 | 0.04 | 0.02 | 0.12 | 0.04 | 0.02 | 0.05 | -0.01 | 0.12 | 0.06 | 0.00 | 0.01 | 0.00 | 0.09 | 0.03 |
| I (Grade C) | i | -0.01 | 0.04 | 0.02 | 0.12 | 0.05 | 0.02 | 0.03 | -0.04 | 0.12 | 0.02 | 0.01 | 0.01 | -0.02 | 0.12 | 0.01 |
| | r | 0.03 | 0.03 | 0.00 | 0.09 | 0.03 | 0.04 | 0.04 | -0.01 | 0.13 | 0.03 | 0.01 | 0.02 | 0.04 | 0.13 | 0.00 |
| W (Grade C) | i | -0.01 | 0.02 | 0.01 | 0.11 | 0.04 | 0.00 | 0.03 | 0.01 | 0.13 | 0.04 | 0.02 | 0.01 | -0.02 | 0.12 | 0.01 |
| | r | 0.02 | 0.04 | -0.03 | 0.11 | 0.04 | 0.03 | 0.05 | 0.01 | 0.11 | 0.02 | 0.05 | 0.04 | -0.03 | 0.09 | 0.01 |
| L (Grade C;low pressure) | i | 0.00 | 0.03 | 0.00 | 0.11 | 0.01 | 0.01 | 0.02 | -0.02 | 0.13 | 0.03 | 0.00 | -0.01 | -0.02 | 0.12 | 0.02 |
| | r | 0.04 | 0.03 | -0.01 | 0.11 | 0.04 | 0.04 | 0.05 | -0.04 | 0.10 | 0.02 | 0.01 | -0.01 | -0.02 | 0.08 | -0.01 |
| Phenolic;rayon fabric | | | | | | | | | | | | | | | | |
| Z | i | -0.02 | 0.01 | -0.01 | 0.07 | 0.05 | 0.01 | 0.00 | 0.00 | 0.08 | 0.04 | 0.00 | 0.03 | -0.03 | 0.07 | 0.02 |
| | r | 0.02 | 0.02 | -0.01 | 0.07 | 0.04 | 0.03 | 0.02 | 0.00 | 0.08 | 0.03 | 0.03 | 0.00 | 0.02 | 0.07 | 0.04 |
| Phenolic;asbestos fabric | | | | | | | | | | | | | | | | |
| K | i | -0.01 | 0.01 | 0.03 | 0.08 | 0.05 | 0.10 | 0.03 | 0.06 | 0.18 | 0.14 | 0.04 | 0.00 | 0.02 | 0.11 | 0.07 |
| | r | 0.02 | 0.00 | -0.01 | 0.06 | 0.03 | 0.04 | 0.07 | 0.03 | 0.16 | 0.14 | 0.02 | 0.01 | 0.04 | 0.10 | 0.10 |
| Melamine: cotton fabric | | | | | | | | | | | | | | | | |
| M | i | 0.02 | 0.01 | -0.02 | 0.09 | 0.03 | 0.03 | 0.03 | 0.00 | 0.11 | 0.07 | 0.01 | -0.02 | 0.00 | 0.12 | 0.01 |
| | r | 0.01 | 0.02 | -0.03 | 0.08 | 0.02 | 0.02 | 0.05 | -0.01 | 0.11 | 0.04 | 0.05 | -0.01 | -0.01 | 0.08 | 0.01 |
| Unsaturated polyester;cotton fabric | | | | | | | | | | | | | | | | |
| F | i | 0.00 | 0.06 | -0.01 | 0.07 | 0.01 | 0.00 | 0.08 | 0.07 | 0.15 | 0.27 | 0.00 | 0.03 | 0.00 | 0.13 | -0.02 |
| | r | 0.01 | 0.06 | 0.01 | 0.09 | 0.00 | 0.01 | 0.04 | 0.04 | 0.13 | 0.15 | 0.00 | 0.02 | -0.01 | 0.11 | 0.02 |
| H | i | 0.00 | 0.01 | 0.01 | 0.16 | 0.05 | 0.02 | 0.05 | 0.04 | 0.29 | 0.17 | 0.03 | 0.03 | 0.02 | 0.18 | 0.09 |
| | r | 0.04 | 0.04 | -0.02 | 0.11 | 0.04 | 0.06 | 0.07 | 0.02 | 0.24 | 0.13 | 0.02 | 0.01 | 0.02 | 0.16 | 0.07 |
| N | i | 0.09 | 0.08 | 0.13 | 0.23 | 0.25 | 0.37 | 0.55 | 0.63 | 0.85 | 0.86 | 0.23 | 0.34 | 0.36 | 0.58 | 0.56 |
| | r | 0.04 | 0.08 | 0.07 | 0.15 | 0.26 | 0.02 | 0.26 | 0.41 | 0.62 | 0.53 | 0.10 | 0.15 | 0.23 | 0.44 | 0.42 |
| Unsaturated polyester;glass-fabric | | | | | | | | | | | | | | | | |
| E | i | 0.03 | 0.04 | 0.02 | 0.06 | 0.04 | 0.03 | 0.09 | 0.08 | 0.09 | 0.10 | -0.01 | -0.02 | 0.03 | 0.05 | 0.04 |
| | r | 0.00 | 0.02 | 0.01 | 0.04 | 0.03 | 0.02 | -0.02 | -0.03 | -0.02 | -0.02 | 0.00 | -0.01 | 0.02 | 0.06 | 0.03 |
| X | i | -0.01 | 0.03 | -0.01 | 0.02 | 0.01 | 0.01 | 0.04 | -0.01 | 0.06 | 0.05 | -0.01 | -0.02 | 0.00 | 0.04 | 0.04 |
| | r | -0.01 | 0.01 | 0.01 | 0.04 | 0.08 | -0.01 | 0.00 | 0.02 | 0.04 | 0.05 | 0.02 | -0.02 | 0.01 | 0.03 | 0.05 |
| Y | i | -0.01 | -0.02 | 0.00 | 0.04 | 0.03 | -0.01 | 0.00 | 0.02 | 0.05 | 0.06 | 0.01 | 0.00 | -0.01 | 0.02 | 0.05 |
| | r | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | -0.02 | 0.00 | 0.02 | 0.05 | 0.05 | 0.01 | 0.01 | 0.04 | 0.03 | 0.02 |
| AA | i | -0.02 | -0.01 | -0.01 | 0.03 | 0.01 | 0.05 | -0.01 | 0.02 | 0.03 | 0.07 | 0.03 | 0.01 | 0.00 | 0.03 | 0.08 |
| | r | -0.03 | 0.01 | 0.00 | 0.01 | 0.02 | -0.02 | -0.03 | 0.00 | 0.04 | 0.02 | 0.01 | -0.03 | 0.03 | 0.04 | -0.02 |
| AB | i | 0.01 | 0.01 | 0.00 | 0.05 | 0.04 | 0.00 | 0.04 | 0.01 | -0.01 | 0.04 | 0.03 | 0.01 | -0.01 | 0.05 | 0.02 |
| | r | 0.02 | 0.01 | -0.01 | 0.06 | 0.03 | -0.03 | 0.00 | -0.02 | 0.04 | 0.03 | 0.02 | 0.02 | 0.00 | 0.06 | 0.01 |

a. Code for this column:
i = Tested immediately.
r = Tested after reconditioning for 7 days at 77° F and 50 percent relative humidity.

b. Based on average value for two specimens

TABLE 5 CHANGES IN THICKNESS OF LAMINATED PLASTICS AFTER CONTINUOUS IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND

| NBS Material Designation | When Tested[a] | Change[b] After Immersion in Heptane For: | | | | | Change[b] After Immersion in Toluene For: | | | | | Change[b] After Immersion in SR-6 For: | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) |
| Lignin paper | | | | | | | | | | | | | | | | |
| D | i | -0.1 | 0.1 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | -0.2 | 0.3 | -0.1 | 0.0 | 0.1 | -0.1 | 0.3 | -0.2 |
| | r | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.0 | 0.4 | -0.1 | 0.1 | 0.2 | -0.1 | 0.4 | -0.2 |
| Phenolic; high-strength paper | | | | | | | | | | | | | | | | |
| C | i | -0.2 | 0.1 | 0.2 | 0.5 | 0.3 | 0.0 | 0.3 | 0.1 | 0.4 | 0.2 | 0.2 | 0.1 | 0.0 | 0.5 | 0.0 |
| | r | -0.4 | 0.1 | 0.2 | 0.2 | 0.3 | 0.1 | 0.4 | 0.2 | 0.5 | 0.2 | 0.3 | 0.3 | -0.1 | 0.4 | 0.1 |
| S | i | -0.1 | 0.1 | 0.1 | 0.4 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 0.0 | 0.0 | 0.1 | 0.4 | 0.0 |
| | r | 0.1 | 0.2 | 0.1 | 0.3 | 0.5 | 0.2 | 0.1 | 0.1 | 0.3 | 0.2 | 0.1 | 0.1 | 0.0 | 0.3 | 0.1 |
| Phenolic; cotton fabric | | | | | | | | | | | | | | | | |
| J (Grade L) | i | -0.2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.3 | 0.2 | 0.0 | 0.2 | 0.2 | -0.2 | 0.2 | -0.1 |
| | r | 0.0 | 0.2 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.2 | 0.0 | 0.0 | -0.2 | 0.1 | 0.0 |
| I (Grade C) | i | -0.1 | 0.2 | 0.1 | 0.2 | 0.0 | -0.1 | 0.2 | -0.2 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.3 | -0.1 |
| | r | 0.1 | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.2 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | -0.1 | 0.2 | -0.2 |
| W (Grade C) | i | 0.0 | 0.0 | 0.0 | 0.1 | -0.1 | 0.0 | 0.2 | 0.0 | 0.1 | 0.2 | 0.0 | 0.1 | -0.1 | 0.3 | 0.0 |
| | r | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.1 | 0.2 | 0.0 | 0.1 | -0.1 | 0.1 | 0.0 | -0.1 | 0.3 | -0.3 |
| L (Grade C; low pressure) | i | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | -0.1 | 0.1 | 0.0 | 0.2 | -0.1 | 0.1 | 0.1 | 0.0 | 0.2 | -0.1 |
| | r | 0.0 | 0.1 | 0.1 | 0.0 | -0.1 | 0.0 | 0.1 | 0.1 | 0.2 | -0.1 | 0.0 | 0.1 | -0.1 | 0.2 | -0.1 |
| Phenolic; rayon fabric | | | | | | | | | | | | | | | | |
| Z | i | -0.1 | 0.0 | 0.1 | 0.4 | 0.3 | 0.0 | 0.3 | 0.2 | 0.3 | 0.3 | 0.0 | -0.1 | 0.1 | 0.2 | 0.1 |
| | r | 0.0 | 0.2 | 0.1 | 0.2 | 0.3 | 0.2 | 0.1 | -0.1 | 0.4 | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 |
| Phenolic; asbestos fabric | | | | | | | | | | | | | | | | |
| K | i | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.4 | 0.3 | 0.4 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 |
| | r | 0.0 | 0.0 | 0.1 | 0.2 | -0.1 | 0.1 | 0.4 | 0.1 | 0.5 | 0.3 | 0.2 | 0.2 | -0.1 | 0.1 | 0.2 |
| Melamine; cotton fabric | | | | | | | | | | | | | | | | |
| M | i | -0.1 | 0.1 | 0.0 | 0.1 | -0.1 | 0.0 | 0.2 | 0.0 | 0.3 | 0.0 | -0.1 | 0.1 | -0.1 | 0.2 | 0.6 |
| | r | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.1 | 0.1 | 0.0 | 0.2 | -0.1 | 0.0 | 0.0 | 0.0 | 0.2 | -0.6 |
| Unsaturated polyester; cotton fabric | | | | | | | | | | | | | | | | |
| F | i | -0.2 | 0.1 | 0.0 | 0.3 | -0.7 | 0.6 | 1.3 | 1.2 | 0.6 | 4.8 | 0.1 | 0.1 | -0.1 | 0.3 | -0.3 |
| | r | 0.1 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 | 0.4 | 2.8 | 0.1 | 0.2 | 0.0 | 0.2 | -0.4 |
| H | i | 0.0 | 0.2 | -0.2 | 0.0 | -0.1 | 0.0 | 0.2 | 0.1 | 0.5 | 0.1 | 0.2 | 0.1 | 0.1 | 0.3 | 0.1 |
| | r | 0.0 | 0.1 | -0.1 | 0.0 | 0.1 | -0.5 | 0.2 | 0.0 | 0.4 | 0.0 | 0.1 | 0.1 | -0.2 | 0.3 | 0.0 |
| N | i | 1.0 | 0.7 | 0.7 | 0.7 | 0.8 | 3.6 | 4.8 | 8.0 | 7.1 | 7.9 | 1.5 | 3.2 | 3.7 | 4.2 | 3.6 |
| | r | -0.1 | 0.7 | 0.0 | 0.7 | 0.3 | 1.5 | 3.2 | 5.0 | 5.7 | 4.6 | 0.7 | 1.7 | 2.4 | 3.8 | 3.1 |
| Unsaturated polyester; glass fabric | | | | | | | | | | | | | | | | |
| E | i | -0.1 | 0.2 | 0.1 | -0.1 | 0.0 | 0.1 | 1.9 | 4.4 | 7.9 | 7.4 | 0.0 | 0.1 | 0.0 | 0.5 | 0.4 |
| | r | -0.1 | 0.2 | 0.1 | 0.1 | 0.1 | -0.1 | 1.2 | 3.0 | 4.9 | 4.5 | 0.2 | 0.2 | 0.0 | 0.2 | 0.3 |
| X | i | -0.1 | 0.0 | 0.2 | 0.0 | 1.0 | 0.0 | 0.1 | 0.1 | 0.6 | 0.3 | -0.2 | 0.1 | 0.0 | 0.1 | -0.1 |
| | r | -0.2 | 0.2 | 0.4 | 0.8 | 0.1 | -0.2 | 0.0 | 0.1 | 0.5 | 0.2 | 0.0 | -0.1 | 0.0 | 0.0 | -0.1 |
| Y | i | 0.1 | 0.0 | -0.1 | 0.3 | 0.0 | 1.0 | 0.2 | 0.6 | 1.2 | 1.0 | 0.0 | 0.3 | 0.1 | 0.3 | 0.1 |
| | r | 0.2 | 0.0 | 0.0 | 0.4 | -0.1 | 0.1 | 0.8 | 0.1 | 0.7 | 0.8 | -0.3 | 0.2 | 0.0 | 0.2 | 0.2 |
| AA | i | 0.1 | 0.0 | 0.1 | 0.2 | 0.1 | 1.2 | 1.9 | 2.2 | 2.7 | 2.7 | 0.2 | 0.4 | 0.6 | 0.9 | 0.2 |
| | r | 0.1 | 0.0 | 0.0 | -0.1 | 0.0 | 0.3 | 0.7 | 1.3 | 2.3 | 1.9 | -0.2 | 0.3 | 0.3 | 0.6 | 1.5 |
| AB | i | 0.0 | 0.1 | 0.0 | -0.1 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.1 | -0.1 | 0.1 | 0.1 | 0.2 | 0.0 |
| | r | 0.0 | 0.2 | 0.0 | 0.1 | -0.6 | 0.2 | 0.2 | -0.1 | 0.2 | 0.0 | -0.2 | 0.2 | 0.0 | 0.0 | -0.2 |

a. Code for this column:
i = Tested immediately.
r = Tested after reconditioning for 7 days at 77° F and 50 percent relative humidity.

b. Based on average value for two specimens.

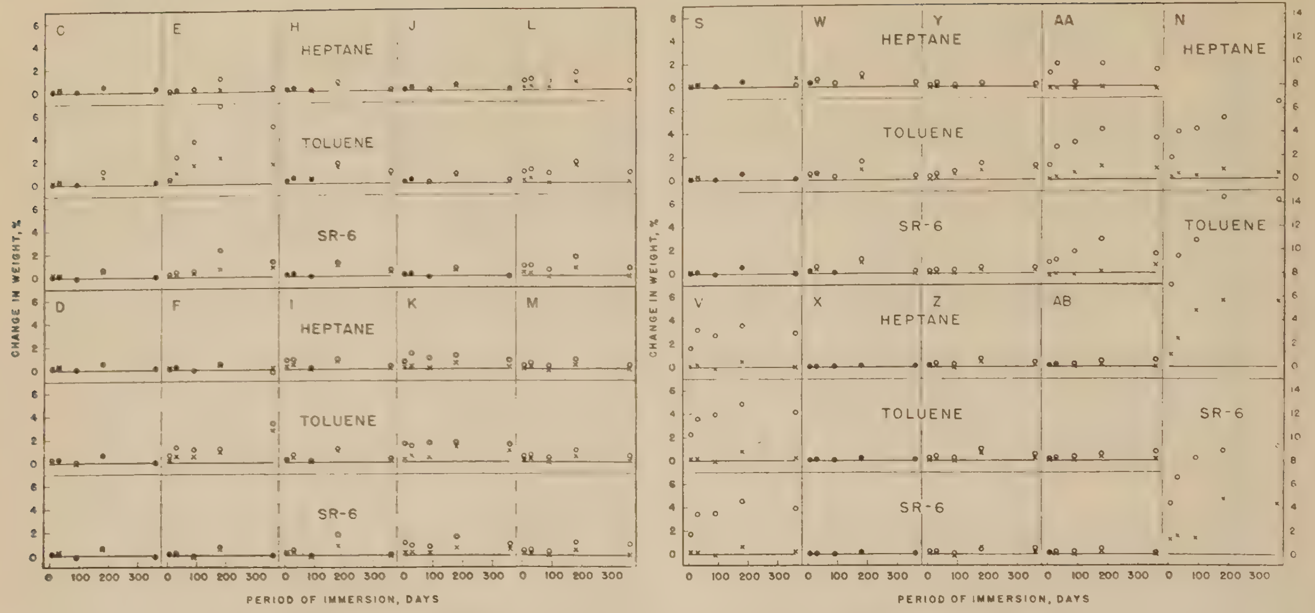

Fig. 3 Changes in Weight of Laminates in Prolonged Fuel-Immersion Tests
(O-tested immediately after removal from the fuel. X-tested after reconditioning for 7 days.)

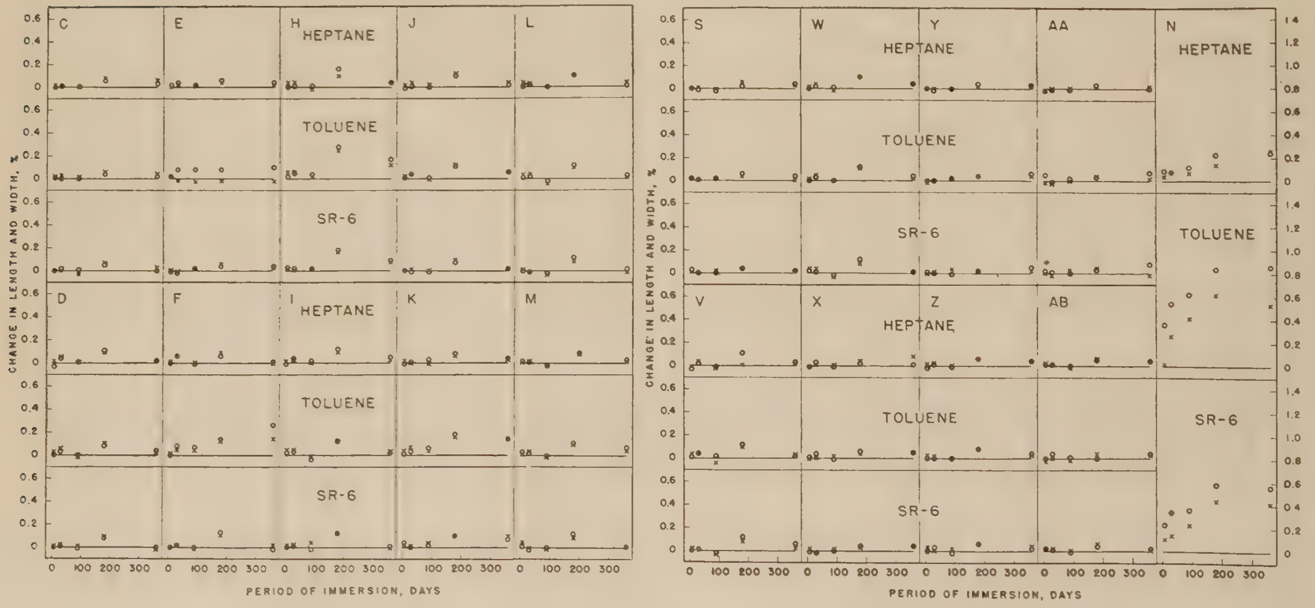

Fig. 4 Changes in Length and Width of Laminates in Prolonged Fuel-Immersion Tests
(O-tested immediately after removal from the fuel. X-tested after reconditioning for 7 days.)

changes, regardless of sign, were equal to or higher for the "tested immediately" condition, as compared with the "reconditioned 7 days" condition in the majority of cases. In the majority of cases toluene caused the greatest changes. In weight and dimensions, the changes in the majority of cases attained their maximum values at the 180-day period. The reduction in the changes during the succeeding 180-day period indicates that the fuels may have dissolved some of the resin.

It is noted that for a given type of laminate, the weight changes varied considerably among the samples. For example, samples J, I, and W are all Grade C laminates made with the same phenolic resin. In most cases the changes for sample W for all three fuels are about double the corresponding values for sample J. Among the glass-fabric unsaturated-polyester laminates, samples E and AA exhibited changes higher than 1 per cent in each of the three fuels during the course of the 360-day immersion tests, compared with sample X which at no time changed as much as 0.3 per cent. The cotton-fabric unsaturated-polyester laminate H showed changes roughly one tenth of those of sample N, a material absorbing greater than 5 per cent of liquid in each of the fuels.

Similar behavior, namely, a wide spread in the changes for samples of a given type of laminate, is evident (Table 5) in the thickness changes of the unsaturated-polyester laminates.

A comparison of the changes in the various samples after 360 days of immersion in the fuels follows:

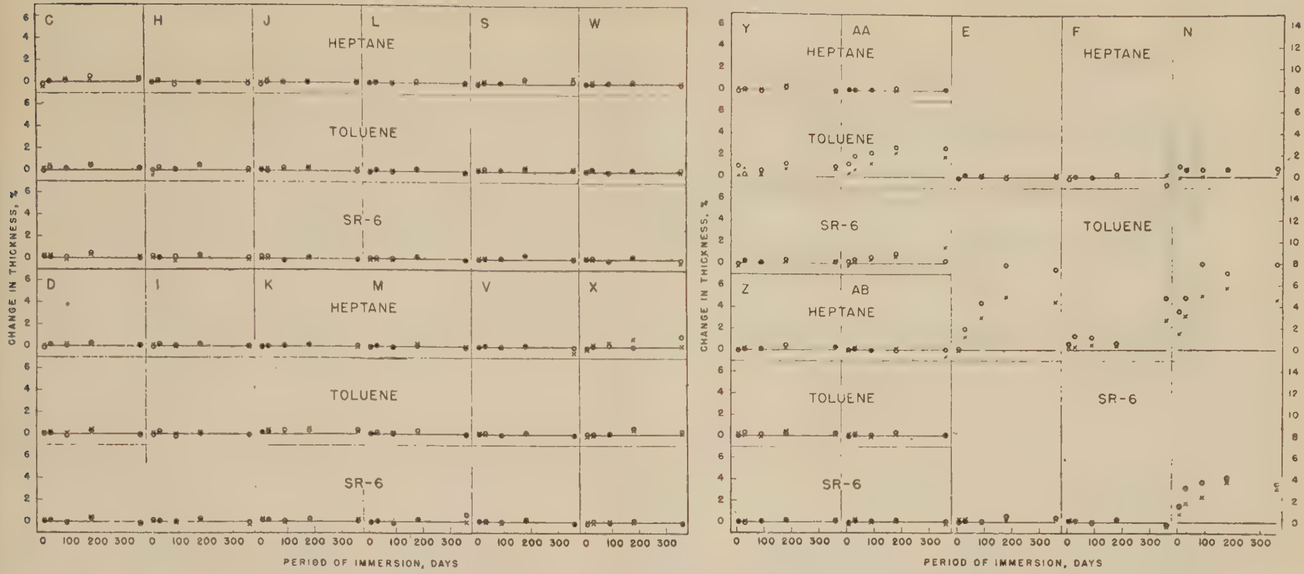

Fig. 5 Changes in Thickness of Laminates in Prolonged Fuel-Immersion Tests

(O-tested immediately after removal from the fuel. X-tested after reconditioning for 7 days.)

*Weight Changes at 360 Days.* In heptane the cotton-fabric unsaturated-polyester laminate N and the glass-fabric unsaturated-polyester laminate AA in the "tested immediately" condition showed changes of 6.60 and 1.44 per cent, respectively. The remainder of the samples exhibited changes of less than 1 per cent, both when tested immediately and after 7 days of reconditioning. In toluene more than one half of the samples when tested immediately and more than three fourths of the materials in tests after reconditioning 7 days showed changes of less than 1 per cent. In SR-6 the laminates N, E, and AA in the tested immediately condition, and the laminate N in the 7-day condition showed changes of 9.32, 1.30, 1.65, and 4.34 per cent, respectively. The remainder of the samples had changes of less than 1 per cent. The lignin paper laminate D, the Grade C phenolic laminate J, and the glass-fabric unsaturated-polyester laminate X have the least average changes for all fuels, and both test conditions with no individual changes greater than 0.3 per cent.

*Length and Width Changes at 360 Days.* The laminate N in heptane and SR-6, and the laminates F, H, K, and N in toluene showed changes greater than 0.1 per cent. The remainder of the samples exhibited changes of 0.1 per cent or less.

*Thickness Changes After 360 Days.* The unsaturated-polyester laminates F, N, and X in heptane, E, F, N, Y, and AA in toluene, and N and AA in SR-6 showed changes greater than 0.6 per cent in either test condition or both. The remainder of the samples had changes of 0.6 per cent or less.

*Changes in Flexural Properties.* The changes in flexural strength and flexural modulus of elasticity of the laminates after immersion in heptane, toluene, and SR-6 are shown in Table 6 for cyclic fuel immersion, and in Tables 7 and 8 and Figs. 6 and 7, for continuous fuel immersion. The laminates exhibiting losses greater than 10 per cent for flexural strength and 5 per cent for flexural modulus of elasticity in the cyclic fuel-immersion test, and after 360 days of continuous fuel immersion are listed in Table 9. The data for the low-pressure Grade C phenolic laminate V were not included in the tables and in the discussion because of its great variability but are shown in Figs. 6 and 7.

(*a*) *Cyclic Fuel-Immersion Test.* In the cyclic fuel-immersion test approximately two thirds of the changes in flexural strength and in flexural modulus of elasticity are negative in each fuel. Considering the changes for each sample in the three fuels, it is noted that the losses are well distributed among the three fuels. The Grade AA phenolic laminate K exhibited the greatest positive changes in all three fuels in both flexural strength and flexural modulus of elasticity, although the initial values of these two properties for sample K are among the lowest.

Of the eighteen samples tested in each fuel, only four, none of which was a cotton-fabric phenolic, had losses in flexural strength greater than 5 per cent. Two samples, the glass-fabric unsaturated-polyester laminate E, and the cotton-fabric unsaturated-polyester laminate N had losses greater than 10 per cent in each of the three fuels.

Approximately one half of the materials exhibited losses in flexural modulus of elasticity less than 5 per cent in each fuel. Only the enameled-cotton-fabric unsaturated-polyester laminate H and the Grade L phenolic laminate J had losses greater than 10 per cent in each of the three fuels.

The samples which showed the greatest flexural stability in the three fuels were the cotton-fabric melamine laminate M, the cotton-fabric phenolic laminate L, the high-strength-paper phenolic laminate S, the cotton-fabric unsaturated-polyester laminate F, and the glass-fabric unsaturated-polyester laminate AB. The changes in both flexural strength and flexural modulus of elasticity did not exceed 5 per cent. Samples X and K, which showed increases but no decreases greater than the foregoing limits, were considered to have withstood the cyclic immersion test favorably. The cotton-fabric unsaturated-polyester laminate N exhibited the greatest changes.

(*b*) *Continuous Fuel-Immersion Test.* In the prolonged fuel-immersion test most of the changes in flexural strength and flexural modulus of elasticity are negative. Eighty per cent of the differences in the percentage values between the "tested immediately" and "reconditioned 7 days" conditions of test for the three fuels in flexural strength and flexural modulus of elasticity are 5 or less. It is considered that differences of this order are not significant. This indicates that in the majority of cases the deterioration occurred during the immersion, and that retained solvent in the tested immediately condition had little effect on the strength and modulus of elasticity. Most of the differences for flexural strength and flexural modulus of elasticity were approximately the same for the three fuels in the two test condi-

TABLE 6 CHANGES IN FLEXURAL PROPERTIES AFTER THE CYCLIC FUEL-IMMERSION TEST[a]

| NBS Material Designation | Initial Flexural Strength[b] ($10^3$ lb/in.$^2$) | Change[c] in Flexural Strength in: | | | Initial Flexural Modulus of Elasticity[b] ($10^6$ lb/in.$^2$) | Change[c] in Flexural Modulus of Elasticity in: | | |
|---|---|---|---|---|---|---|---|---|
| | | Heptane (%) | Toluene (%) | SR-6 (%) | | Heptane (%) | Toluene (%) | SR-6 (%) |
| Lignin paper | | | | | | | | |
| D | 23.5±0.4 | -7 | -8 | -3 | 1.92±0.05 | -10 | -5 | -4 |
| Phenolic; high-strength paper | | | | | | | | |
| C | 35.1±0.4 | -4 | -7 | -9 | 2.57±0.03 | -8 | -5 | -4 |
| S | 33.7±0.3 | -2 | -2 | -1 | 2.47±0.01 | -4 | -5 | -1 |
| Phenolic; cotton fabric | | | | | | | | |
| J (Grade L) | 17.4±0.2 | 3 | 3 | 1 | 1.12-0.04 | -13 | -11 | -12 |
| I (Grade C) | 22.9±0.3 | -2 | -2 | -1 | 1.24±0.02 | -8 | -3 | -6 |
| W (Grade C) | 20.7±0.2 | 8 | 3 | -1 | 1.20±0.04 | 0 | -10 | -7 |
| L (Grade C; low pressure) | 20.7±0.1 | 5 | 2 | 2 | 1.02±0.03 | -4 | 2 | 1 |
| Phenolic; rayon fabric | | | | | | | | |
| Z | 46.4±0.5 | -2 | -3 | -4 | 2.22±0.04 | -9 | -9 | -7 |
| Phenolic; asbestos fabric | | | | | | | | |
| K | 9.0±0.1 | 19 | 9 | 11 | 0.99±0.06 | 5 | 10 | 10 |
| Melamine; cotton fabric | | | | | | | | |
| M | 25.4±0.6 | -2 | -3 | 0 | 1.62±0.02 | -3 | 2 | 1 |
| Unsaturated polyester; cotton fabric | | | | | | | | |
| F | 16.1±0.4 | -4 | -3 | -4 | 0.71±0.02 | -2 | -1 | 2 |
| H | 13.1±0.1 | -4 | -3 | -6 | 0.67±0.02 | -14 | -12 | -12 |
| N | 12.1±0.2 | -12 | -19 | -20 | 0.45±0.01 | -8 | -22 | -16 |
| Unsaturated polyester; glass fabric | | | | | | | | |
| E | 34.1±0.1 | -13 | -16 | -14 | 1.81±0.04 | -9 | -17 | 1 |
| X | 41.2±0.3 | 2 | 5 | 5 | 1.68±0.01 | 4 | 6 | 9 |
| Y | 34.5±0.2 | -6 | -5 | -4 | 1.44±0.02 | 2 | 1 | 0 |
| AA | 20.3±0.9 | 11 | 0 | 4 | 1.82±0.05 | -6 | -10 | -8 |
| AB | 56.5±0.9 | -3 | 3 | 1 | 2.86±0.02 | 0 | -3 | 1 |

a. Each cycle of the test consists of a 24-hour immersion and a 24-hour drying period. Flexural tests were made after 10 cycles of test and reconditioning at 77°F. and 50 percent relative humidity for 48 hours.

b. Average value for six specimens. The accompanying plus and minus value is the standard error.

c. Based on average value for four specimens.

TABLE 7 CHANGES IN FLEXURAL STRENGTH OF LAMINATED PLASTICS AFTER CONTINUOUS IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND

| NBS Material Designation | Initial Flexural Strength[a] $(10^3 lb/in^2)$ | When Tested[b] | Change[c] After Immersion in Heptane for: 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | Change[c] After Immersion in Toluene for: 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | Change[c] After Immersion in SR-6 for: 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lignin paper | | | | | | | | | | | | | | | | | |
| D | 23.5±0.4 | i | -3 | -5 | -4 | -6 | -3 | -6 | -5 | -7 | 3 | 0 | -13 | -6 | -6 | -5 | -6 |
| | | r | -8 | -9 | -7 | -3 | -3 | 0 | -6 | -4 | -3 | -2 | -6 | -1 | -2 | -5 | -6 |
| Phenolic; high-strength paper | | | | | | | | | | | | | | | | | |
| C | 35.1±0.4 | i | -5 | -6 | -9 | -17 | -9 | -5 | -7 | -7 | -9 | -5 | -5 | -8 | -6 | -11 | -9 |
| | | r | -9 | -1 | -5 | -7 | -7 | -4 | -3 | -9 | -10 | -9 | -13 | 0 | -7 | -10 | -9 |
| S | 33.7±0.3 | i | -4 | -9 | -3 | -2 | -2 | 0 | 3 | -6 | -3 | -3 | -5 | 0 | -3 | -4 | -3 |
| | | r | -7 | -6 | -6 | -1 | -2 | -2 | -6 | -5 | -3 | -3 | 3 | -3 | -3 | -4 | -7 |
| Phenolic; cotton fabric | | | | | | | | | | | | | | | | | |
| J (Grade L) | 17.4±0.2 | i | -1 | 1 | -1 | -1 | -1 | 1 | 3 | 2 | 0 | -2 | 2 | 5 | -6 | 3 | 2 |
| | | r | 1 | 0 | -1 | -5 | -1 | 1 | 0 | 1 | 1 | -1 | -1 | 3 | 0 | -3 | 1 |
| I (Grade C) | 22.9±0.3 | i | -10 | -9 | -2 | -4 | -5 | -3 | -3 | -6 | -5 | -4 | -2 | -3 | -7 | -7 | -6 |
| | | r | -5 | -3 | -1 | -7 | -5 | 0 | -2 | -6 | -3 | -6 | -2 | -5 | -5 | -8 | -7 |
| W (Grade C)- | 20.7±0.2 | i | -4 | -1 | -7 | -1 | -4 | -3 | -4 | -2 | -2 | 1 | -1 | 1 | -6 | -5 | -1 |
| | | r | -2 | 2 | -3 | 0 | -1 | -3 | 7 | -3 | -1 | -4 | 1 | 3 | -2 | -3 | -5 |
| L (Grade C; low pressure) | 20.7±0.1 | i | -2 | -2 | -1 | 3 | 2 | -1 | 3 | 1 | 2 | 1 | -4 | 3 | 0 | -1 | -1 |
| | | r | -7 | -1 | 10 | 1 | 1 | -5 | -2 | 1 | 1 | 1 | -3 | 1 | 17 | 1 | -1 |
| Phenolic; rayon fabric | | | | | | | | | | | | | | | | | |
| Z | 46.4±0.5 | i | -6 | -4 | -6 | -3 | -4 | -8 | -5 | -6 | -5 | -5 | -3 | -3 | -3 | -6 | -7 |
| | | r | -4 | -2 | -4 | -2 | -4 | -2 | -3 | -5 | -4 | -4 | 0 | 0 | -5 | -5 | -7 |
| Phenolic; asbestos fabric | | | | | | | | | | | | | | | | | |
| K | 9.0±0.1 | i | 11 | 11 | 4 | 13 | 17 | 13 | 21 | 18 | 20 | 18 | 6 | 19 | 15 | 12 | 11 |
| | | r | 11 | 8 | 17 | 20 | 10 | 13 | 11 | 14 | 9 | 21 | 6 | 11 | 10 | 13 | 9 |
| Melamine; cotton fabric | | | | | | | | | | | | | | | | | |
| M | 25.4±0.6 | i | -4 | -5 | -6 | -2 | -7 | -3 | -4 | -7 | -6 | -4 | -6 | -7 | -5 | -4 | -7 |
| | | r | -7 | -5 | -8 | -4 | -6 | -2 | -5 | -11 | -4 | -6 | -6 | -8 | -3 | -5 | -1 |
| Unsaturated polyester; cotton fabric | | | | | | | | | | | | | | | | | |
| F | 16.1±0.4 | i | -3 | -6 | -4 | 1 | -4 | -6 | -11 | -13 | -5 | -30 | -1 | -1 | -1 | -9 | -3 |
| | | r | -6 | -7 | -4 | -2 | -5 | -2 | -2 | -11 | -5 | -20 | -15 | -9 | -11 | -7 | -2 |
| H | 13.1±0.1 | i | -3 | -6 | -3 | -2 | -6 | -5 | 0 | -9 | -7 | -8 | -5 | -3 | -7 | -11 | -8 |
| | | r | -4 | -5 | -8 | -4 | -9 | -1 | -2 | -5 | -6 | -11 | -5 | -1 | -5 | -7 | -8 |
| N | 12.1±0.2 | i | -19 | -29 | -19 | -9 | -17 | -44 | -37 | -34 | -41 | -46 | -32 | -40 | -37 | -36 | -31 |
| | | r | -17 | -21 | -17 | -7 | -16 | -34 | -28 | -30 | -34 | -30 | -22 | -30 | -21 | -29 | -28 |
| Unsaturated polyester; glass fabric | | | | | | | | | | | | | | | | | |
| E | 34.1±0.1 | i | -12 | -13 | -21 | -28 | -14 | -15 | -32 | -46 | -53 | -50 | -16 | -15 | -24 | -27 | -24 |
| | | r | -12 | -12 | -14 | -22 | -14 | -11 | -24 | -36 | -41 | -38 | -13 | -12 | -22 | -20 | -25 |
| X | 41.2±0.3 | i | 4 | 5 | -2 | -2 | -4 | 5 | 4 | -2 | -6 | -3 | 7 | 7 | -1 | -7 | -10 |
| | | r | 7 | 5 | -5 | -4 | -3 | 7 | 4 | -1 | -5 | -2 | 7 | 8 | -6 | -6 | -5 |
| Y | 34.5±0.2 | i | -11 | -10 | -14 | -9 | -13 | -11 | -13 | -16 | -21 | -20 | -11 | -11 | -15 | -15 | -18 |
| | | r | -11 | -8 | -11 | -8 | -10 | -3 | -9 | -17 | -16 | -20 | -7 | -7 | -14 | -11 | -16 |
| AA | 20.3±0.9 | i | -2 | -3 | -3 | 4 | -2 | -5 | -13 | -16 | -20 | -18 | 1 | 8 | -3 | -7 | -2 |
| | | r | 5 | 9 | 5 | 5 | 2 | -6 | -3 | -6 | -7 | -10 | 3 | 7 | -4 | -3 | -1 |
| AB | 56.5±0.9 | i | -4 | 1 | -8 | -5 | -9 | -5 | -1 | -7 | -7 | -7 | 0 | -3 | -8 | -6 | -9 |
| | | r | -5 | [illegible] | -3 | -2 | -10 | -5 | -2 | -10 | -7 | -10 | -2 | -1 | -8 | 1 | -9 |

a. Average value for six specimens. The accompanying plus or minus value is the standard error.

b. Code for this column:
i = Tested immediately.
r = Tested after reconditioning for 7 days at 77°F and 50 percent relative humidity.

c. Based on average value for four specimens.

TABLE 8 CHANGES IN FLEXURAL MODULUS OF ELASTICITY OF LAMINATED PLASTICS AFTER CONTINUOUS IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND

| NBS Material Designation | Initial Flexural Modulus of Elasticity[a] ($10^6$ lb/in.$^2$) | When Tested[b] | Change[c] after Immersion in Heptane for: | | | | | Change[c] after Immersion in Toluene for: | | | | | Change[c] after Immersion in SR-6 for: | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) | 7 Days (%) | 30 Days (%) | 90 Days (%) | 180 Days (%) | 360 Days (%) |
| Lignin paper | | | | | | | | | | | | | | | | | |
| D | 1.92 ± 0.05 | i | - 8 | -10 | -11 | 0 | - 1 | -10 | -11 | 0 | 14 | 4 | -13 | - 3 | 1 | 0 | - 1 |
| | | r | -11 | - 9 | - 2 | - 6 | 3 | -12 | - 4 | - 2 | 6 | 3 | -10 | 9 | - 5 | - 2 | -10 |
| Phenolic; high-strength paper | | | | | | | | | | | | | | | | | |
| C | 2.57 ± 0.03 | i | - 8 | -11 | -10 | -14 | 3 | - 5 | -11 | - 5 | 3 | 4 | - 8 | - 8 | - 2 | 2 | 0 |
| | | r | - 9 | -10 | - 4 | - 1 | 2 | - 9 | - 8 | 0 | - 2 | - 1 | -10 | 7 | - 5 | 0 | - 3 |
| S | 2.47 ± 0.01 | i | - 8 | - 3 | 0 | 6 | 6 | - 6 | 2 | - 1 | - 1 | 9 | - 5 | 6 | - 1 | 9 | 6 |
| | | r | - 8 | -10 | - 4 | 1 | 8 | - 6 | - 8 | 0 | - 1 | 4 | - 7 | 0 | - 1 | 8 | 5 |
| Phenolic; cotton fabric | | | | | | | | | | | | | | | | | |
| J (Grade L) | 1.12 ± 0.04 | i | -20 | -14 | - 9 | - 5 | -2 | -16 | -14 | - 4 | 1 | 0 | -16 | -16 | - 3 | - 1 | 3 |
| | | r | -15 | -16 | - 6 | 5 | 1 | -13 | -14 | - 2 | - 6 | 2 | -18 | -10 | - 2 | 5 | - 1 |
| I (Grade C) | 1.24 ± 0.02 | i | -22 | -17 | 2 | 2 | 0 | -13 | - 9 | - 6 | - 4 | - 1 | -10 | -11 | - 2 | - 5 | 2 |
| | | r | -14 | - 8 | 1 | - 6 | 0 | -10 | - 6 | 0 | 0 | 2 | -16 | 1 | 0 | -10 | 3 |
| W (Grade C) | 1.20 ± 0.04 | i | -15 | - 8 | - 2 | -11 | - 2 | -17 | -19 | - 3 | -15 | 0 | -12 | 7 | - 5 | - 2 | - 4 |
| | | r | -15 | -11 | - 9 | - 9 | - 2 | -16 | - 1 | - 3 | - 6 | - 5 | -16 | - 8 | - 9 | - 4 | 6 |
| L (Grade C; low pressure) | 1.02 ± 0.03 | i | - 5 | - 4 | 8 | - 5 | 4 | - 3 | - 4 | 3 | 8 | 6 | - 4 | - 3 | 7 | 5 | 4 |
| | | r | - 7 | - 5 | 1 | 7 | 0 | -10 | - 3 | 4 | 1 | 7 | - 7 | 4 | 5 | 6 | 4 |
| Phenolic; rayon fabric | | | | | | | | | | | | | | | | | |
| Z | 2.22 ± 0.04 | i | -14 | -13 | -11 | - 8 | - 4 | -13 | -13 | - 7 | - 8 | - 2 | -13 | -10 | - 2 | - 4 | - 4 |
| | | r | -17 | -15 | -12 | - 8 | - 3 | -15 | - 9 | - 9 | - 3 | - 5 | -15 | - 7 | -11 | - 5 | - 5 |
| Phenolic; asbestos fabric | | | | | | | | | | | | | | | | | |
| K | 0.99 ± 0.06 | i | 7 | 8 | - 4 | 15 | 22 | -10 | 12 | 9 | 23 | 19 | -14 | 7 | 15 | 8 | 21 |
| | | r | 9 | - 2 | 12 | 19 | 18 | 9 | 10 | 16 | 11 | 18 | - 6 | 9 | 13 | 12 | 20 |
| Melamine; cotton fabric | | | | | | | | | | | | | | | | | |
| M | 1.62 ± 0.02 | i | - 7 | - 4 | 1 | - 3 | 3 | - 1 | - 4 | 3 | 3 | 5 | - 4 | - 1 | 1 | 0 | 2 |
| | | r | - 3 | - 5 | - 2 | 3 | 3 | - 6 | - 5 | -10 | 0 | 4 | - 5 | 1 | 0 | 3 | 3 |
| Unsaturated polyester; cotton fabric | | | | | | | | | | | | | | | | | |
| F | 0.71 ± 0.02 | i | - 5 | - 3 | 16 | 19 | 19 | - 9 | -20 | - 7 | 8 | -31 | - 7 | 1 | 16 | 3 | 5 |
| | | r | - 6 | - 5 | 14 | 16 | 16 | - 5 | - 4 | 2 | 13 | -20 | -26 | 7 | 4 | 7 | 16 |
| H | 0.67 ± 0.02 | i | -10 | -12 | - 5 | 10 | - 5 | -12 | 1 | -10 | - 9 | -11 | -11 | -11 | -10 | - 4 | - 3 |
| | | r | -12 | -11 | - 7 | 5 | 0 | -10 | -10 | -10 | -11 | - 7 | -12 | 1 | - 7 | - 3 | 2 |
| N | 0.45 ± 0.01 | i | -14 | -21 | - 6 | 1 | - 1 | -48 | -46 | -39 | -47 | -48 | -30 | -30 | -35 | -25 | -26 |
| | | r | -17 | -16 | - 8 | - 1 | - 1 | -29 | -29 | -37 | -34 | -31 | -16 | -23 | -14 | -20 | -23 |
| Unsaturated polyester; glass fabric | | | | | | | | | | | | | | | | | |
| E | 1.81 ± 0.04 | i | - 4 | - 5 | -18 | -22 | 3 | -12 | -32 | -40 | -41 | -37 | -10 | -10 | -10 | -16 | -11 |
| | | r | - 9 | - 5 | - 4 | -18 | - 3 | - 8 | -25 | -32 | -41 | -33 | - 2 | 0 | -17 | - 2 | -11 |
| X | 1.68 ± 0.01 | i | 4 | 4 | 0 | 4 | 7 | 5 | 7 | 4 | 3 | 10 | 5 | 8 | 5 | 8 | - 4 |
| | | r | 8 | 9 | 1 | 3 | 28 | 5 | 5 | 0 | 3 | 8 | 4 | 17 | - 3 | 7 | 8 |
| Y | 1.44 ± 0.02 | i | - 5 | 2 | - 2 | 0 | 5 | - 2 | 3 | 1 | - 1 | 2 | - 3 | 1 | 1 | - 1 | 4 |
| | | r | - 3 | - 1 | - 4 | 1 | 6 | 4 | 2 | 0 | - 6 | - 1 | 0 | - 2 | - 4 | 0 | 10 |
| AA | 1.82 ± 0.05 | i | -14 | -20 | 1 | - 5 | - 5 | -23 | -26 | - 6 | -13 | -14 | -14 | - 9 | -10 | -10 | - 4 |
| | | r | - 8 | - 9 | 9 | - 3 | 6 | -28 | - 9 | - 6 | -14 | -11 | -12 | - 8 | - 9 | - 3 | 1 |
| AB | 2.86 ± 0.02 | i | - 7 | - 7 | - 9 | - 9 | - 1 | - 9 | - 8 | -18 | - 4 | - 6 | - 7 | - 3 | - 1 | - 2 | - 6 |
| | | r | -11 | -12 | - 7 | - 3 | - 5 | -11 | - 5 | - 9 | - 6 | - 5 | - 8 | - 4 | - 3 | - 5 | - 3 |

a. Average value for six specimens. The accompanying plus or minus value is the standard error.

b. Code for this column: i = Tested immediately.
r = Tested after reconditioning for 7 days at 77°F and 50 percent relative humidity.

c. Based on average value for four specimens.

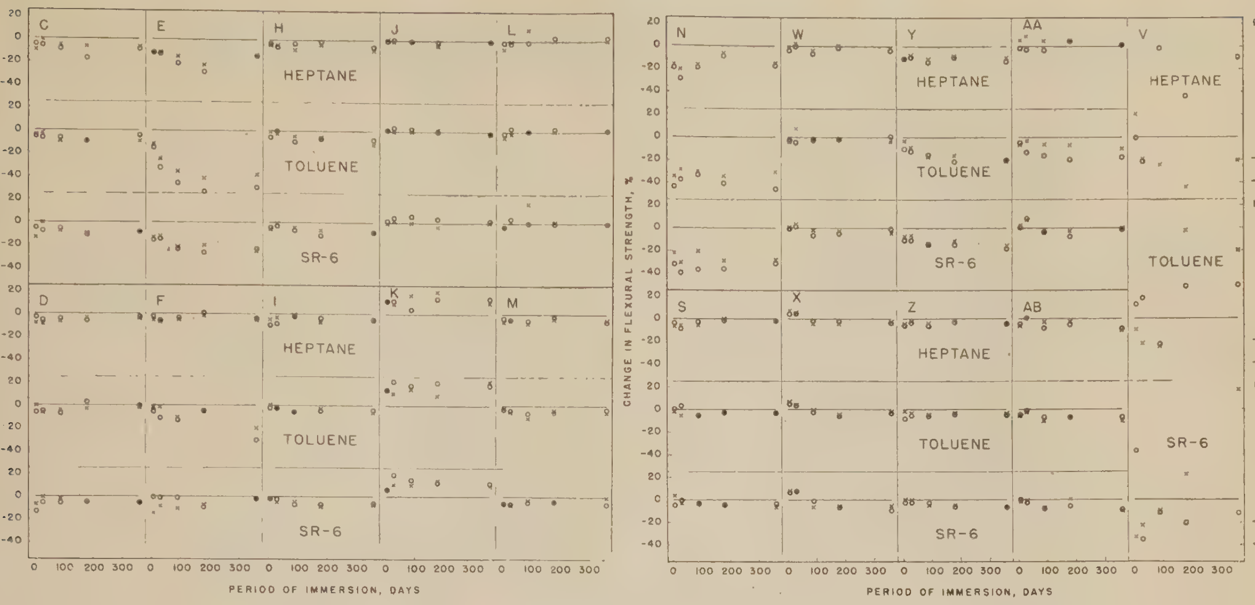

FIG. 6 CHANGES IN FLEXURAL STRENGTH OF LAMINATES IN PROLONGED FUEL-IMMERSION TESTS
(O-tested immediately after removal from the fuel. X-tested after reconditioning for 7 days.)

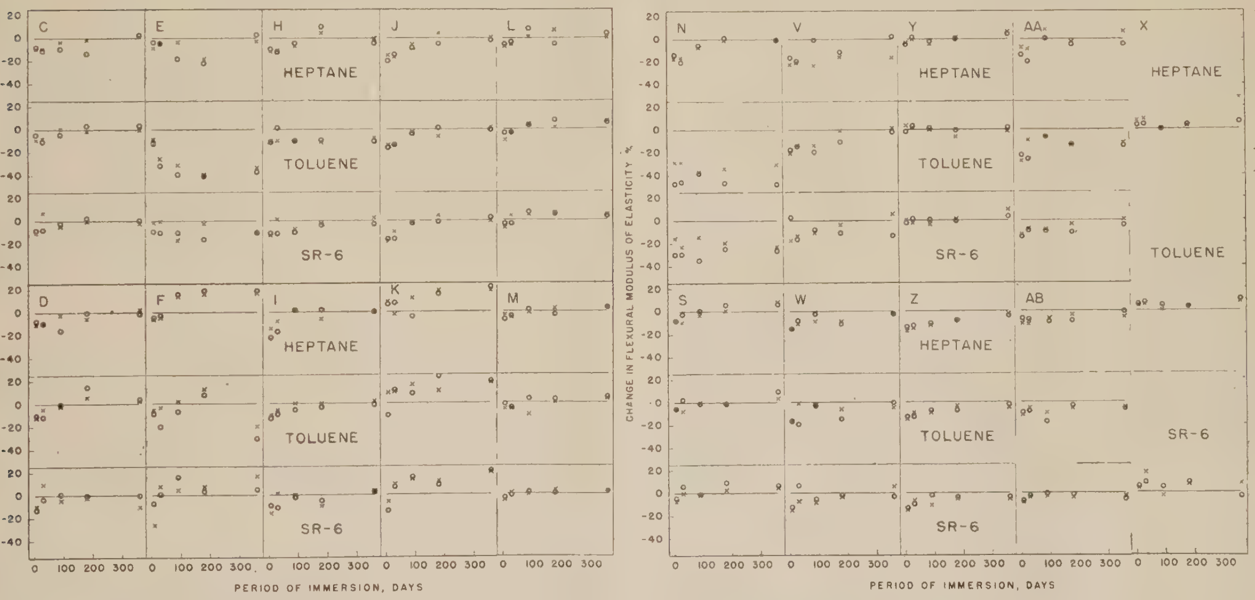

FIG. 7 CHANGES IN FLEXURAL MODULUS OF ELASTICITY OF LAMINATES IN PROLONGED FUEL-IMMERSION TESTS
(O-tested immediately after removal from the fuel. X-tested after reconditioning for 7 days.)

tions; where there were exceptions, the differences were usually greatest in toluene. Most of these large differences took place in the unsaturated-polyester laminates.

At no time during the continuous-immersion test, did any cotton-fabric phenolic laminate show losses in flexural strength exceeding 10 per cent in the three fuels. This was also true of two glass-fabric unsaturated-polyester materials, X and AB, the paper-phenolic laminate S, and the rayon-phenolic laminate Z. The cellulose-filled phenolic laminates exhibited the following trend with regard to the flexural modulus of elasticity in the course of the immersion tests: After 7 days of immersion, the changes were losses, and as the test progressed the losses decreased with some samples showing gains at the end of the test. The changes for the cotton-fabric phenolic materials were about —10 to — 20 per cent at 7 days, and at 360 days the changes were about —5 to +5 per cent.

It is noted that, just as in the cyclic-immersion test, the various samples of polyester laminates varied considerably in their flexural-strength behavior on prolonged immersion.

A comparison of the changes in the flexural properties of the various samples after 360 days of immersion in the fuels follows:

*Flexural Strength Changes at 360 Days.* In heptane only the unsaturated-polyester laminates E, N, and Y showed losses greater than 10 per cent. In toluene the only samples that showed losses greater than 10 per cent in either test condition were all unsaturated-polyester laminates. Samples X and AB were the only materials of this type which did not exceed 10 per cent loss. In SR-6 only the unsaturated-polyester laminates E, N,

TABLE 9 SAMPLES WITH CHANGES IN PROPERTIES GREATER THAN SELECTED VALUES INDICATED IN THIS TABLE AFTER IMMERSION IN HEPTANE, TOLUENE, AND SR-6 FUEL BLEND[a]

| Property | Heptane | Toluene | SR-6 |
|---|---|---|---|
| Weight (> ±1 per cent change): | | | |
| Cyclic immersion.......... | ... | N | N |
| Continuous immersion, 360 days: | | | |
| Tested immediately....... | N, AA | E, F, H, K, N, Y, AA | E, N, AA |
| Reconditioned............ | ... | E, F, N, Y | N |
| Length and width (> ± 0.1 per cent change): | | | |
| Cyclic immersion.......... | N | N | N |
| Continuous immersion, 360 days: | | | |
| Tested immediately....... | N | F, H, K, N | N |
| Reconditioned............ | N | F, H, K, N | N |
| Thickness (> ±0.5 per cent change): | | | |
| Cyclic immersion.......... | AA | N, AA | I, L, M |
| Continuous immersion, 360 days: | | | |
| Tested immediately....... | F, N, X | E, F, N, Y, AA | M, N |
| Reconditioned............ | AB | E, F, N, Y, AA | M, N, AA |
| Flexural strength (> —10 per cent change): | | | |
| Cyclic immersion.......... | E, N | E, N | E, N |
| Continuous immersion, 360 days: | | | |
| Tested immediately....... | E, N, Y | E, F, N, Y, AA | E, N, Y |
| Reconditioned............ | E, N | E, F, H, N, Y | E, N, Y |
| Flexural modulus of elasticity (> —5 per cent change): | | | |
| Cyclic immersion.......... | C, D, E, H, I, J, N, Z, AA | E, H, J, N, W, Z, AA | H, I, J, N, W, Z, AA |
| Continuous immersion, 360 days: | | | |
| Tested immediately....... | ... | E, F, H, N, AA, AB | E, N, AB |
| Reconditioned............ | ... | E, F, H, N, AA | D, E, N |

[a] The letters are the designations for the laminates tested as shown in Table 1. Due to the variability of the V material, it was not included in this summary.

and Y showed losses greater than 10 per cent. In each of the three fuels and for both test conditions, nearly one half of the samples had losses greater than 5 per cent. The Grade AA phenolic laminate K was the only material which exhibited increases for both test conditions in each of the three fuels.

*Flexural Modulus of Elasticity Changes at 360 Days.* In heptane none of the samples exhibited losses greater than 5 per cent for either test condition. In toluene the unsaturated-polyester laminates X and Y showed losses of 1 per cent or less in either test condition. The remaining unsaturated-polyester laminates showed losses of 5 per cent or more. In SR-6 the only samples which had losses greater than 5 per cent in either test condition were the unsaturated-polyester laminates E, N, and AB, and the lignin-paper laminate D. The phenolic laminates K, L, and S, and the melamine laminate M were the only samples which exhibited increases for both test conditions in all three fuels, and the phenolic laminate K had the largest increases.

The only sample which exhibited changes not exceeding 5 per cent[5] in both flexural strength and modulus of elasticity after 360 days of immersion in each fuel was sample J. Other samples exhibiting satisfactory behavior were the asbestos-fabric phenolic laminate K, which exhibited positive changes, and the cotton-fabric phenolic laminates L and W, which showed no losses greater than 5 per cent but whose increases were more than 5 per cent in some instances. The cotton-fabric unsaturated-polyester resin laminate N showed the greatest losses in flexural properties.

## CONCLUSIONS

The following conclusions refer to the actual numerical results obtained in this investigation. Since there may be appreciable differences in the properties of individual sheets taken from the same batch, in different batches made by the same manufacturer, and in similar laminates made by different manufacturers, any general inferences drawn from these data about a given type of laminate should be considered tentative.

1 No one sample exhibited smaller changes than all the other samples in all properties for all fuels and for both cyclic and continuous immersion.

2 In all three fuels, the weight changes of the majority of the laminates were less than 1 per cent in the cyclic test, and did not exceed 1.5 per cent after 360 days of continuous immersion. The largest weight changes were usually obtained with the unsaturated-polyester laminates in toluene.

3 With very few exceptions, mainly cotton-fabric unsaturated-polyester samples, the length and width changes after either the cyclic or the 360-day immersion in the fuels did not exceed 0.1 per cent. In both types of test the changes in thickness were, in the majority of cases, less than 1 per cent. The exceptions occurred mainly in the 360-day immersion test for several unsaturated-polyester laminates in toluene.

4 The best weight and dimensional stability in all three fuels in the cyclic test was observed with the glass-fabric unsaturated-polyester laminate X.

5 After the 360-day immersion test, the weight and dimensional changes were, in the majority of cases, higher for the samples when tested immediately as compared with measurements after reconditioning for 7 days.

6 The changes in flexural strength for the cyclic test and after the 360-day immersion test were, in the majority of cases, negative. However, the losses were less than 10 per cent for all samples, except some unsaturated-polyester laminates. For the latter samples in the 360-day test, greater losses usually occurred in toluene than in the other fuels.

7 The changes in flexural modulus of elasticity were, in the majority of cases, negative in the cyclic and the continuous-immersion tests. In the cyclic test no losses greater than 10 per cent were shown by the samples, except one phenolic laminate and several unsaturated-polyester samples. After 360 days of immersion, no losses greater than 10 per cent occurred except for some unsaturated-polyester laminate samples in toluene or in SR-6 or in both.

8 The unsaturated-polyester laminate samples varied widely among themselves in regard to the magnitude of the change in a given property after the immersion tests.

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[5] Changes in the flexural properties less than 5 per cent are not considered significant due to the variability of the material.

# Current Design Practices for Gas-Turbine Power Elements

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**A brief description is presented of certain principles of design and analysis for power elements of commercial gas-turbine plants. These principles are based upon the experience of the gas-turbine engineering group of the author's company. The discussion comprises a review of procedures for analysis of turbine performance and design of blading and blade-carrying elements. Since the mechanical reliability and useful service life of a gas-turbine plant are governed almost entirely by the design of the power element, such a design must be a compromise between requirements for high efficiency, dependability, and low first cost. The fulfillment of these requirements is assisted by the organization of fundamental principles and experience into basic design practices.**

## INTRODUCTION

NUMEROUS technical discussions have been published concerning the general features and potentialities of gas-turbine plants for land, marine, and air service. This paper is restricted to the consideration of a single component of the gas-turbine plant, namely, the basic power element. The problems under discussion comprise (*a*) the design of the turbine blade path from the standpoint of fluid mechanics, and (*b*) the basic principles of stress analysis used for the blades and blade-carrying elements. The mechanical construction of such parts as casings, bearings, supports, and governors is not included.

## GENERAL DESIGN PRINCIPLES

*Importance of Optimum Design.* The net output of a gas-turbine plant is represented by a surplus in power produced by an expansion element over the power demand of a compression element. On an average, the ratio of gross power to net power is of the order of 2 or 3 to 1. Assuming a constant compressor demand, an increase of 1 per cent in turbine efficiency results in a gain of from 2 to 3 per cent in net output and efficiency. This indicates the importance of improving power-element performance to the maximum practical level.

Mechanical reliability and useful service life of a gas-turbine plant are governed to a large degree by the design of the power element. In this element occurs the particularly critical combination of high temperature and high dynamic stress. Reliability and long life are of primary importance for commercial turbines. These requirements are reflected by a tendency toward conservatism in temperature and stresses in such machines when compared with aircraft-turbine practice. Since performance requirements for commercial applications do not permit any appreciable sacrifice in fuel economy, it is necessary to offset the effects of moderate cycle temperatures by increasing power-element efficiencies at some expense in over-all weight and size.

*Basic Turbine-Design Principles.* The most important factors which control the type of construction adopted for any specific gas turbine are as follows:

(*a*) Desired efficiency level.
(*b*) Expected useful service life.
(*c*) Required maximum-load capability.
(*d*) Desirable variable-load characteristics.

The particular problems associated with commercial applications indicate that certain design principles have definite advantages:

1 The premium placed on performance almost invariably results in the employment of a multistage construction. Turbine efficiency is thereby considerably improved over the level which can be obtained with the lightweight single-stage turbines ordinarily used in aircraft units.

2 The large volumetric flows inherent in high-capacity designs necessitate correspondingly large annular flow areas. These are best provided by high ratios of active blade height to blade-ring mean diameter. Three-dimensional flow considerations therefore become of considerable importance, and the mechanical design of the blading and spindle becomes more difficult.

3 High speeds are desirable to reduce physical size as much as possible. Procurement of large ingots is difficult with many of the better gas-turbine alloys. In addition, handling and fabricating problems in the shops increase rapidly with size of part.

The foregoing principles lead to the conclusion that the most practical design for commercial application is one incorporating a plurality of stages, employing maximum blade-height ratios in the low-pressure elements, and rotating at a maximum speed. Fig. 1 shows a cross section through the blade path of such a turbine, this particular design being representative of units intended for commercial power applications.

## BLADE-PATH DESIGN AND PERFORMANCE ANALYSIS

*Turbine Efficiency.* The internal efficiency of a turbine relates the actual power produced by the turbine stages to the theoretical power available in an isentropic expansion from the total pressure and temperature at the turbine inlet to the static pressure at the turbine exhaust. It is a function of the following basic variables

$$\eta_i = (\eta_s)(RF) - \%\Delta h_L \ldots\ldots\ldots\ldots\ldots [1]$$

where

$\eta_i$ = internal efficiency, per cent
$\eta_s$ = average stage efficiency, per cent
$RF$ = reheat factor
$\%\Delta h_L$ = leaving loss, per cent

The stage efficiency takes into account the losses incurred in each element due to gas friction and leakage. It is primarily dependent upon the operating conditions and configuration of the staging, and it can be controlled within fairly wide limits by the designer.

The reheat factor originates from the fact that as the gas

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 48-A-170.

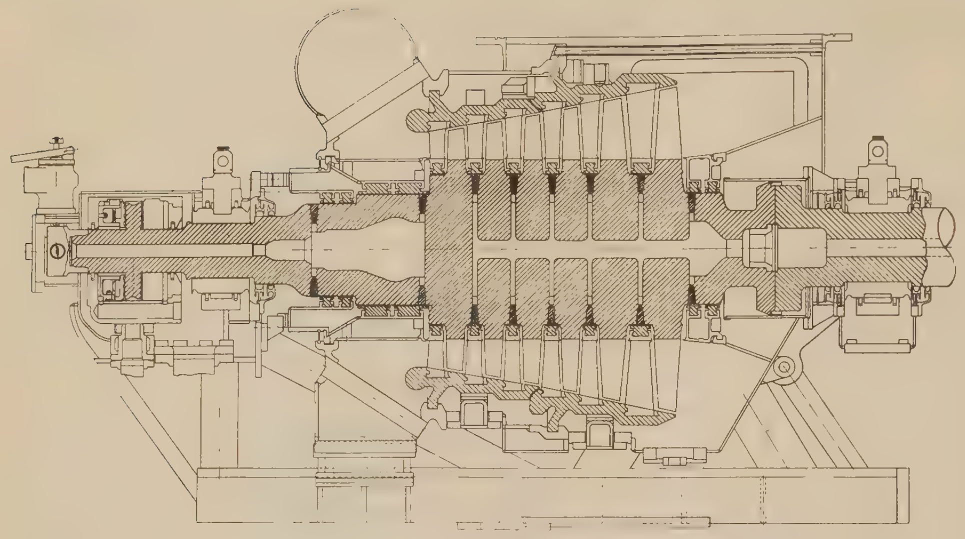

Fig. 1 Cross Section Through Typical Commercial Gas-Turbine Power Element

progresses through the blading, friction and leakage cause the actual temperatures to be slightly above those corresponding to an expansion without losses. This has an apparent effect of increasing the over-all efficiency slightly above the incremental stage efficiency. Fig. 2 shows a reheat-factor plot computed from the following formula (1)[2]

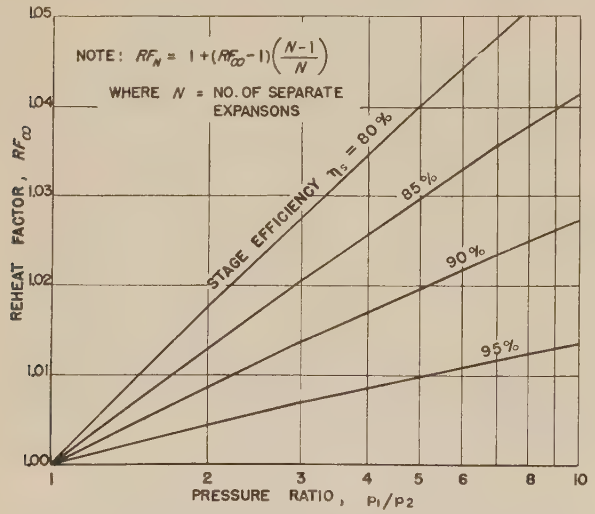

Fig. 2 Reheat Factors for Gas-Turbine Expansions
(Curves are based upon a mean-specific-heat ratio of 1.350.)

$$RF_\infty = \frac{1}{\eta_s}\left[\frac{1-\left(\dfrac{p_2}{p_1}\right)^{\eta_s \frac{k-1}{k}}}{1-\left(\dfrac{p_2}{p_1}\right)^{\frac{k-1}{k}}}\right] \qquad [2]$$

where

$RF_\infty$ = reheat factor for infinite stages
$p_1$ = turbine inlet pressure
$p_2$ = turbine exhaust pressure
$k$ = mean-specific-heat ratio

Leaving loss is proportional to the residual kinetic energy contained in the gas leaving the turbine. Shaft power is generally the only useful output from a commercial gas turbine, and residual kinetic energy is unavailable for further use. The magnitude of the leaving loss is primarily dependent upon the relation between the total volumetric flow of gas and the annular flow area at the last row of blades. The large volumetric flow in high-capacity units necessitates the use of a considerable amount of exhaust annulus area if the leaving loss is to be held to an acceptable value.

*Stage Performance.* Both theory and experience indicate that the following basic factors almost completely control the performance of an individual stage:

1 Primary factors: (*a*) Isentropic velocity ratio
(*b*) Stage reaction
(*c*) Leakage configuration
2 Secondary factors: (*a*) Pressure ratio
(*b*) Parasitic losses
(*c*) Viscosity effects

Numerous tests have shown that isentropic velocity ratio is the most important criterion establishing general performance level of a stage, regardless of the actual physical configuration. This parameter measures the energy loading for the stage and is defined by the following relation

$$\frac{u}{c_0} = \sqrt{\frac{\Delta h_u}{\Delta h_s}} \qquad [3]$$

where

$u$ = blade velocity at blade-ring mean diameter, fps
$c_0$ = gas velocity corresponding to stage isentropic enthalpy drop, fps
$\Delta h_u$ = stage equivalent blading energy, Btu per lb
$= \dfrac{u^2}{2gJ}$
*$\Delta h_s$ = stage isentropic enthalpy drop, Btu per lb
$g$ = 32.17 ft/sec²
$J$ = 778.26 ft-lb/Btu

For a given set of blading operating with a moderate pressure drop, changes in flow kinematics within the blading are adequately reflected by changes in the isentropic velocity ratio. Fig. 3 shows two examples of basic blading-efficiency curves as derived by test. Curves such as these represent blading performances only, and stage efficiencies ordinarily will be somewhat lower due to the effects of other factors.

As a general rule, the number of stages to be employed in a specific turbine design is determined from the selection of a

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[2] Numbers in parentheses refer to the Bibliography at the end of the paper.

* Reaction-turbine designers customarily use the isentropic drop per row, rather than per stage, in Equation [3]. However, the use of the stage drop is more general in application.

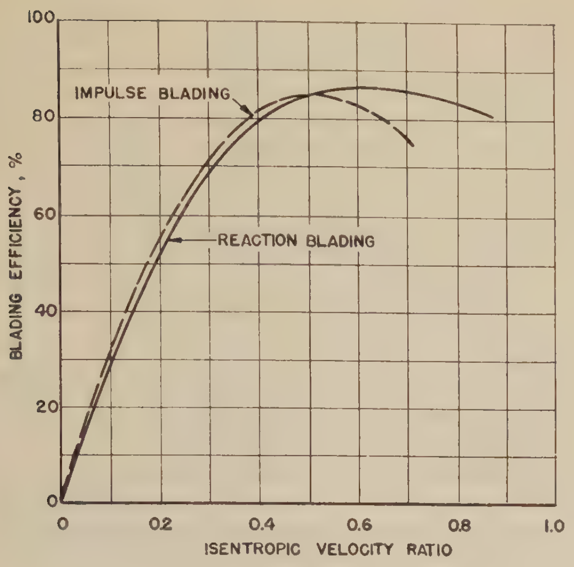
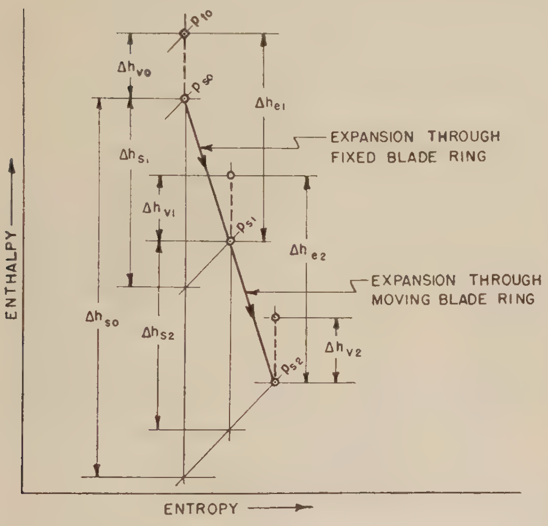


Fig. 3 Typical Blading-Efficiency Curves



$\Delta h_{v0}$ = KINETIC ENERGY ENTERING STAGE
$\Delta h_{s0}$ = STAGE ISENTROPIC ENTHALPY DROP
$\Delta h_{s1}$ = ISENTROPIC ENTHALPY DROP ACROSS FIXED BLADE RING
$\Delta h_{e1}$ = EFFECTIVE KINETIC ENERGY LEAVING FIXED BLADE RING
$\Delta h_{v1}$ = KINETIC ENERGY ENTERING MOVING BLADE RING (RELATIVE TO MOVING BLADE RING)
$\Delta h_{s2}$ = ISENTROPIC ENTHALPY DROP ACROSS MOVING BLADE RING
$\Delta h_{e2}$ = EFFECTIVE KINETIC ENERGY LEAVING MOVING BLADE RING (RELATIVE TO MOVING BLADE RING)
$\Delta h_{v2}$ = KINETIC ENERGY LEAVING STAGE

Fig. 4 Enthalpy-Entropy Diagram of Stage Expansion

desirable velocity ratio at the normal operating load. The curves in Fig. 3 show that high velocity ratios are required for good efficiency. However, the number of stages rises rapidly as the velocity ratio increases. A considerable amount of investigation of each design is necessary to obtain a satisfactory balance in this respect.

The second major factor affecting stage performance is the stage reaction. This parameter is best explained by reference to Fig. 4 which shows the energy quantities in a stage on an enthalpy-entropy diagram. The expansion through a stage is accomplished in two distinct steps, namely, a partial expansion through the fixed blade ring, followed by an additional expansion through the moving blades. The distribution of energy assigned to these two successive expansions is at the control of the designer and is established by means of the stage reaction. Stage reaction is defined as the ratio of the isentropic enthalpy drop across the moving blades to the isentropic enthalpy drop across the stage.

Two opposing considerations influence the amount of reaction used in a specific turbine. Purely from the performance standpoint, it is preferred to use a stage reaction of approximately one half. This corresponds to the conditions in normal reaction blading, and maximum efficiency is obtained provided velocity ratio is high and leakage losses are low. If the turbine isentropic enthalpy drop is large, the number of stages may become excessive. When this occurs it is frequently desirable to decrease the number of stages by decreasing the average velocity ratio of the high-pressure elements. The reaction in these elements is also lowered, and they assume the form of a normal impulse-blading configuration. This is particularly desirable when high temperatures and stresses are involved, since a reduction in stage reaction lowers the effective impact temperature on the moving blades.

Leakage control plays a dominant part in establishing stage efficiency level. Gas leakage through operating clearances between rotating and stationary parts represents a loss of working fluid. It is therefore desirable that clearances be kept to the minimum value consistent with reliability, and that the leakage gas path be made as tortuous as possible.

Both shrouded and open-ended blades are used. For blades operating at high tip velocities, shroud weight adds considerably to the centrifugal stress at the blade base. If the blade is long, the leakage and end-loss effects can be kept small and at the same time safe operating clearances at the blade tip can be maintained. Open-ended construction is preferred in such a design (see Fig. 1). Leakage control for short blades is better if shrouding is installed.

Spindle glands are normally designed with step-type labyrinth seals similar to those shown in Fig. 1. This same construction is used for interstage seals in disk-and-diaphragm blade paths. Accurate tests have been made and correlated by simple theory (2) to determine the leakage characteristics of various types of seals. The performance with air of a typical standard labyrinth design is summarized in Fig. 5.

Pressure ratio is listed as a secondary factor influencing stage performance. For single-stage turbines, pressure ratio may become of major importance. Compression shock losses and poor control of fluid direction may seriously depreciate efficiency

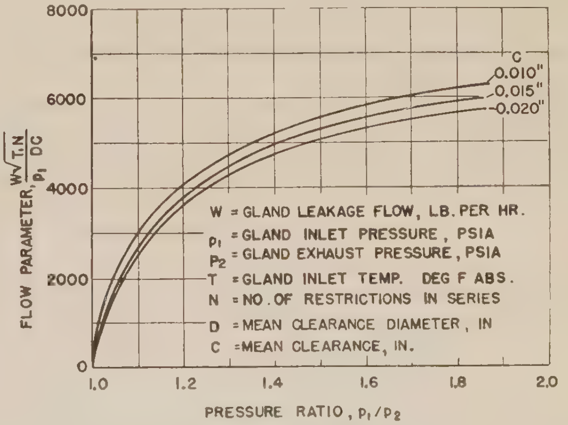


Fig. 5 Leakage Flow Chart—Summary of Tests of Step-Type Spring-Back Labyrinth Seal

when high pressure drops are employed across individual elements. However, the pressure ratio across each stage of a multistage turbine is generally small, with a corresponding decrease in influence on the individual elements. The Mach number of the mean fluid stream relative to the blading seldom exceeds about 0.65. This magnitude causes little difficulty due to shock or choking as long as the flow is accelerated.

Parasitic losses resulting from disk or spindle gas friction are not high in gas turbines of the type under consideration. However, they are accounted for in performance estimation through empirical formulas derived from test analysis.

The influence of viscous forces within turbine staging is measured by the Reynolds number. Laboratory tests on small turbine elements are known to indicate a Reynolds-number effect, but the importance of this factor has not been apparent from tests on full-scale commercial turbines. The influence is sufficiently small in large units so as to be indeterminate in the presence of other more powerful factors.

*Basic Stage Analysis.* Requirements for optimum performance at high speed make it necessary in most cases to design the blading configuration for a new turbine to conform to a specific application. It is therefore essential that there be available detailed procedures for turbine-stage analysis. The designer is thereby able to predict the approximate actual conditions existing within each element and can proportion the blades accurately with respect to shape and setting.

Blading analyses by means of filament-flow theory and vector diagrams are as old as the steam-turbine art, but these conceptions still represent the most powerful tools available to the practical gas-turbine designer. Two basic requirements must be met in applying vector diagrams to blading performance and flow analysis:

1 The velocity magnitudes must represent integrated mean values rather than highly peaked or depressed local values.

2 The velocity directions must represent mean fluid directions, and not necessarily blade-profile geometric angles.

Cascade tests have contributed to a certain extent to the alignment of current design information, but the main source of data has always been analyses of over-all turbine tests. Actual working procedures are admittedly oversimplified from the viewpoint of the highly developed mathematics of modern aerodynamics. It cannot be assumed that the actual flow conditions within a stage are in exact agreement with predictions from simplified vector-diagram analyses. However, reasonable correspondence between prediction and performance has been thoroughly demonstrated, provided suitable control is exerted by continual comparison with test results.

The basic variables in blade-ring calculations are shown in Fig. 6. The data apply to either fixed or moving blades, provided the velocity magnitudes and directions are taken relative to the blade ring under consideration. The most important quantity required in blade-ring analysis is the effective kinetic energy at the ring outlet. This energy is computed from the following relation

$$\Delta h_{e2} = \phi^2_E(\Delta h_{s2} + C_i\phi^2_v\Delta h_{v1}) \ldots\ldots\ldots\ldots [4]$$

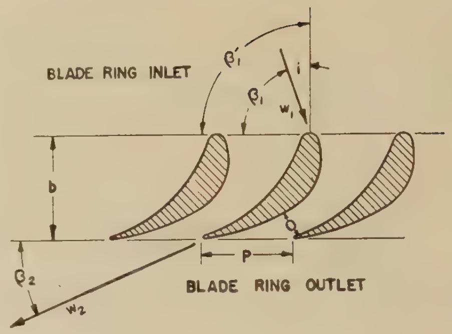
where

$\phi^2_E$ = expansion-energy coefficient
$C_i$ = incidence coefficient
$\phi^2_v$ = kinetic-energy coefficient
See Fig. 6 for other symbols.

The primary loss resulting from turbulence and wall friction within the blade passage is reflected by the expansion-energy coefficient. This coefficient is determined from the profile width and deflection angle, as shown in Fig. 7. Tests indicate that the effective energy obtained from a given amount of inlet kinetic energy is less than that which is realized when the same quantity of available energy is supplied by pressure drop. In Equation [4] the inlet kinetic energy is reduced by a kinetic-energy coefficient. This coefficient is normally assumed to be equal to the expansion-energy coefficient. The rule is rough, but it is justified by an elementary theory of blade friction loss. (3). When the inlet velocity vector forms a definite incidence angle with reference to the blade leading edge, an additional loss occurs which is evaluated by means of the incidence coefficient. This coefficient is a function of the blade-nose design and the angle of incidence as shown in Fig. 8.

The angle of efflux from the ring is assumed to be approximately equal to arcsine $(O/P)$, where $O$ is the blade throat opening and $P$ is the blade circumferential pitch. The accuracy of this simple rule is adequate for small efflux angles. It is discussed in more detail in a later section.

Establishment of the average velocity magnitudes and directions within a stage permit the determination of tangential velocity components. Estimated blading output per pound of gas flow may then be found by entering these data into the basic turbine equation



BLADE RING DATA:—

$b$ = AXIAL WIDTH, IN.
$\beta_1'$ = BLADE INLET ANGLE, DEG.
$O$ = THROAT OPENING, IN.
$P$ = CIRCUMFERENTIAL PITCH, IN.
$O/P$ = OPENING COEFFICIENT
$\beta_2$ = ANGLE OF EFFLUX, DEG. $\cong \sin^{-1}(O/P)$ (SEE FIG. 12)
$\theta$ = DESIGN DEFLECTION ANGLE, DEG. $= 180° - (\beta_1' + \beta_2)$

GAS FLOW DATA: —

$\beta_1$ = GAS INLET ANGLE, DEG
$i$ = INCIDENCE ANGLE, DEG. $= \beta_1' - \beta_1$
$w_1$ = INLET VELOCITY, FPS
$w_2$ = EFFECTIVE OUTLET VELOCITY, FPS
$\Delta h_{v1}$ = KINETIC ENERGY AT INLET, BTU/LB.
$\Delta h_{s2}$ = ISENTROPIC ENTHALPY DROP, BTU/LB.
$\Delta h_{e2}$ = EFFECTIVE KINETIC ENERGY AT OUTLET, BTU/LB.

Fig. 6 Blade-Ring Analysis

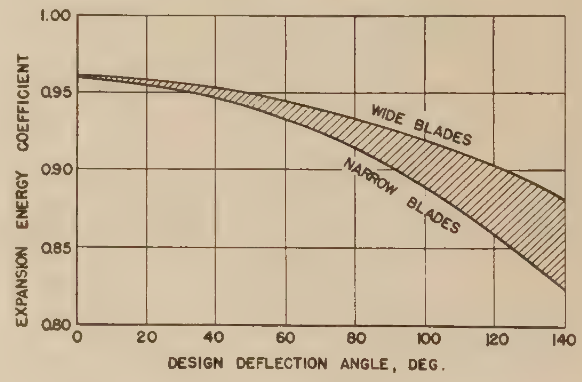


Fig. 7 Variation of Expansion-Energy Coefficient With Design Deflection Angle

$$\Delta h'_w = \frac{u_1 c_{t1} - u_2 c_{t2}}{gJ} \quad [5]$$

where

$\Delta h'_w$ = blading output, Btu per lb
$u_1$ = blade velocity adjacent to the fixed-ring outlet mean diameter, fps
$u_2$ = blade velocity at the outlet mean diameter of the moving ring, fps
$c_{t1}$ = tangential component of effective velocity leaving fixed ring, fps
$c_{t2}$ = tangential component of velocity leaving stage, fps

The gas flow is found from the continuity equation using the effective velocity, area, and gas density at the blade-ring throat. Net stage output may then be calculated by subtracting clearance and parasitic losses from the gross blading output.

*Three-Dimensional Considerations.* Radial variations in circumferential pitch between blades increase as the blading is lengthened. If the blades are installed with normal pitch at the blade-ring mean diameter, the pitch at the tip may become excessive and result in poor control of fluid direction. At the inner radii, the pitches may become so small as to restrict the gas considerably. Furthermore, unless the flow is controlled properly, the tangential velocity components along the outlet plane of the fixed blade ring tend to throw the fluid outward. This centrifugal action results in a massing of the flow toward the tips and a starving of the blade passages at the roots.

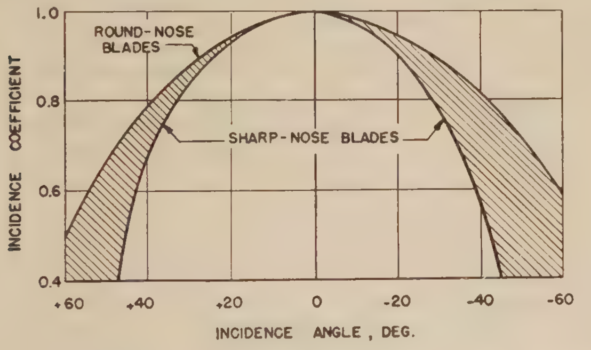


FIG. 8 VARIATION OF INCIDENCE COEFFICIENT WITH INCIDENCE ANGLE

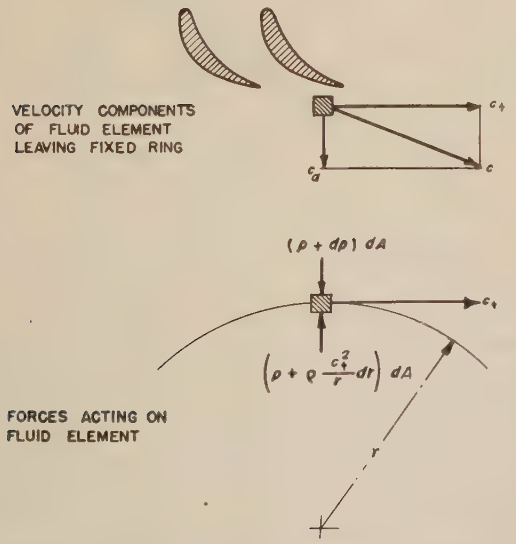

VELOCITY COMPONENTS OF FLUID ELEMENT LEAVING FIXED RING
$c_t$
$c_a$
$c$
$(p + dp)\, dA$
$c_t$
$\left(p + \rho \frac{c_t^2}{r} dr\right) dA$
FORCES ACTING ON FLUID ELEMENT
$r$

FIG. 9 VELOCITY COMPONENTS AND FLUID FORCES AT FIXED-BLADE-RING OUTLET

The three-dimensional flow problem has been attacked quite thoroughly using approaches based on aerodynamic theory. For practical purposes, however, a simple and adequate solution is obtainable from rather elementary conceptions. The basic elements of the problem are presented in Fig. 9. The upper diagram shows the velocity components of a fluid stream leaving a fixed ring of blades at a given radius. In the lower diagram the same velocities are projected onto the outlet plane of the blades. Consideration of the forces acting on an incremental mass of gas indicates that the static pressure at the fixed-ring outlet must gradually increase with radius in accordance with the following equation

$$\frac{dp}{dr} = \rho \frac{c^2_t}{r} \quad [6]$$

where

$p$ = static pressure at fixed-ring outlet, psfa
$r$ = radius, ft
$\rho$ = mass density of gas, lb-sec²/ft⁴
$c_t$ = tangential component of velocity leaving fixed ring, fps

Three controlling premises are made in the practical design of blading where special provision is to be incorporated for maintenance of radial equilibrium:

1 The basic equation for radial stability of flow, as given in Equation [6], is to be satisfied over the entire outlet plane of the fixed blade ring.

2 The mass flow through the stage is to be distributed evenly over the entire stage annulus.

3 The isentropic enthalpy drop across the stage is to be constant at all radii in the stage annulus.

Stages designed in accordance with these conceptions exhibit the following characteristics:

1 The fixed blades have almost symmetric profiles at all radii.

2 The moving-blade profiles vary with radius. At the inner radius, the profile shape approaches that of a normal impulse blade. An approximately normal reaction-blade profile is used at the mean radius. At the tip, the profile assumes the form of a low-cambered airfoil of medium thickness.

Analyses of tests on both steam and gas turbines incorporating such blading have indicated that appreciable improvements in efficiency are attained in comparison with more conventional designs. In addition, improved accuracy has been obtained with respect to prediction of mass-flow characteristics.

*Turbine Performance.* The performance of a complete turbine depends primarily upon the characteristics of the individual stages composing the turbine. However, it is essential that the design be established and controlled from the standpoint of the complete unit, rather than as an assembly of completely independent elements. Poor design of any one stage affects elements both upstream and downstream from that point. The residual kinetic energy from each stage except the last is available to the succeeding stage. With adequate care in design, this energy is recoverable to a large extent.

Other factors than stage design may have appreciable effects on performance. Pressure drops in the inlet and exhaust passages are particularly important. Low velocities, gentle changes in flow direction, and freedom from obstructions are essential if harmful reductions in both performance and load capability are to be prevented (4). Radiation losses may reach significant values in high-temperature units, particularly at light load. Adequate insulation is mandatory, not only for the turbine proper but also for all interconnecting piping handling hot gas. Mechanical losses, as imposed by bearings, reduction gears, and lubrication and governor oil pumps, are generally small for commercial gas turbines.

Over-all turbine performance is determined analytically by combining the results of stage calculations and then correcting for the external effects just discussed. Dimensional analysis assists in correlating the influences of the various factors. For practical purposes the performance of a given turbine can be represented adequately in terms of the following simplified parameters

$$\left(\frac{W\sqrt{T_{t1}}}{p_{s2}}\right), (\eta_i) = f\left(\frac{p_{t1}}{p_{s2}}\right), \left(\frac{n}{\sqrt{T_{t1}}}\right) \ldots\ldots\ldots [7]$$

where

$W$ = gas flow, lb per hr
$T_{t1}$ = total temperature at inlet, deg F abs
$p_{t1}$ = total pressure at inlet, psia
$p_{s2}$ = static pressure at exhaust, psia
$\eta_i$ = internal efficiency, per cent
$n$ = turbine speed, rpm

Fig. 10 is a general performance map in terms of these parameters for a turbine rated at 12,000 gross bhp. The calculation of such a chart represents the final step in the thermodynamic analysis of each turbine design. The accuracy of the over-all design procedure is measured by the degree of correlation on such a chart between computed and test performance.

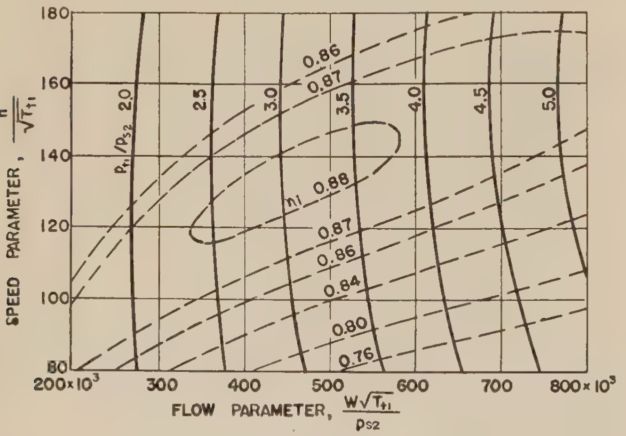


Fig. 10 Typical Gas-Turbine Power-Element Performance Map

## Turbine-Blade Design

*Standard Blade Profiles.* Each steam-turbine manufacturer has conducted over a period of years extensive shop and field tests on the blading configurations used in his particular turbine designs. These programs have resulted in a standardization within each company of not only blade profiles but also blade pitches and settings for the best compromise between efficiency and cost (5).

A number of commercial gas turbines have been built utilizing standard blade profiles of various types. These machines have given excellent performance within their normal ranges of application. The general trend, however, has been toward higher rotative speeds with the accompanying advantages of reduced size and weight. Ratios of blade length to mean diameter are of necessity increased in such machines, and considerations of both three-dimensional flow effects and blade stresses have led to the general adoption of blades with warped surfaces and high degrees of taper. Standard profiles are, therefore, not ordinarily applicable, and each new turbine design requires special profile development to some degree.

*Basic Profile-Design Principles.* The significant dimensions and angles used to control profile design are illustrated in Fig. 11. The most important parameter is the opening coefficient, which is defined as the ratio of the minimum passage width or throat opening between adjacent blades to the circumferential pitch of the blades. Control of both fluid efflux angle and mass flow is exerted primarily by means of the opening coefficient. As long ago as 1924, test data published by the Steam Nozzles Research Committee in England (6) showed that, for the particular nozzles and blades tested, the fluid angle was given quite closely by arcsine $(O/P)$. Subsequent tests, both published and unpublished, have verified this approximate relationship within a reasonable range. General experience indicates that the curve in Fig. 12 provides a relatively accurate guide. The curve shows an increasing deviation of the fluid angle from arcsine $(O/P)$ as the opening coefficient is increased.

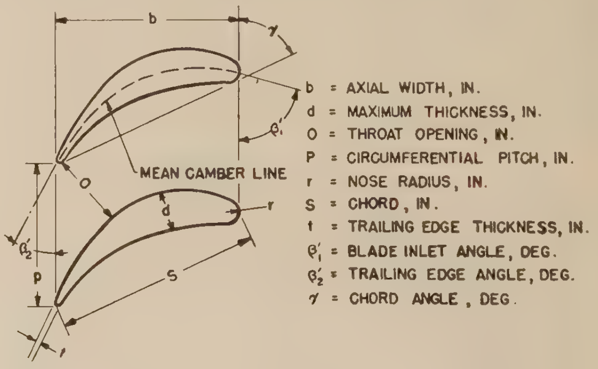

b
γ
β₁'
MEAN CAMBER LINE
O
d
r
β₂'
P
S
t
b = AXIAL WIDTH, IN.
d = MAXIMUM THICKNESS, IN.
O = THROAT OPENING, IN.
P = CIRCUMFERENTIAL PITCH, IN.
r = NOSE RADIUS, IN.
S = CHORD, IN.
t = TRAILING EDGE THICKNESS, IN.
β₁' = BLADE INLET ANGLE, DEG.
β₂' = TRAILING EDGE ANGLE, DEG.
γ = CHORD ANGLE, DEG.

Fig. 11 Profile and Blade-Ring Nomenclature

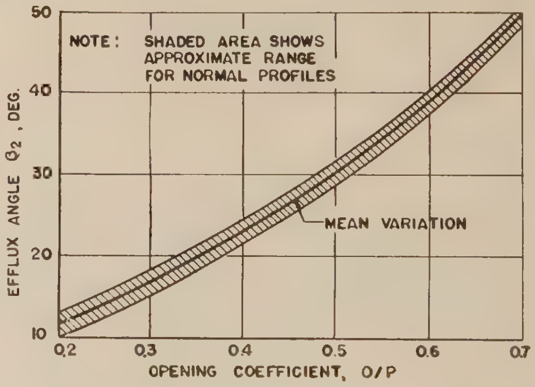


Fig. 12 Variation of Efflux Angle With Opening Coefficient

Blading performance is affected to a large extent by the aerodynamic loading on the profiles. The resultant force acting on a profile corresponds to the integrated pressure differences between the convex and concave surfaces. In closely pitched blades, these pressure differences and their accompanying turbulence losses are reduced. However, losses due to surface friction are increased. Wide pitching decreases surface-friction loss, but aerodynamic loading is increased. This may induce stalling with an accompanying rapid drop in performance.

Aerodynamic loading is a function of the cascade solidity or chord/pitch ratio. The permissible ranges of blading solidity for standard profiles have been fairly accurately established by test. Complete correlation of test results has not been attained for all types of profiles over the range from sharp-edged high-deflection impulse blades to low-camber small-deflection airfoils. However, sufficient data to permit interpolation between known optimum settings have been assembled and interpreted in terms of an aerodynamic loading coefficient (7).

For the practical design of a blade, vector diagrams at control points along the blade height are established from the data in the previous sections. The requirements for fixed blade rings are generally such that normal reaction profiles can be used. The contours, pitches, and settings at all radii are established from experience with such configurations. The vector diagrams for long moving blades require that the profiles be varied along the radius. The fluid deflection angle at the blade base is generally large, and highly cambered, closely pitched profiles must be used. Depending upon the stress conditions and the root design, a ratio of circumferential pitch to axial width of from 0.45 to 0.60 is ordinarily selected. The profile at the tip is normally designed as a low-camber airfoil of medium thickness. The aerodynamic loading coefficient is brought into use here, the solidity being established such that the loading coefficient does not exceed a permissible maximum value.

*Blade Layout.* Required blade pitches, throat openings, and axial widths or chords are established by application of the principles described in the previous paragraphs. Profiles are then laid out with the following considerations for guidance:

1 The stress in a blade due to centrifugal force is proportional to the blade volume above the point of stress. Profile thicknesses and cross-sectional areas must therefore be closely controlled within limits prescribed by preliminary stress analysis.

2 Geometric inlet and outlet angles are set at approximately the desired fluid angles. Exact correspondence is not necessary and is seldom obtained. The selection of inlet angle varies with the partial-load performance requirements for the stage and turbine.

3 Profile nose design depends upon stress conditions and fluid velocities. Moderately small nose radii are ordinarily prescribed. Trailing-edge thicknesses are consistent with the particular manufacturing process to be used and vary from approximately 1 per cent of the chord to not over 8 per cent of the throat opening.

It is considered essential that the passage area between adjacent blades converge at all points in the direction of flow. The walls of the passage as formed by the blade surfaces are kept free of sharp changes in radius of curvature. The actual contours of the profiles are described by combinations of either circular arcs or parabolic arcs, depending upon the desired degree and rate of change of curvature. Fig. 13 shows a set of profiles designed in accordance with these principles.

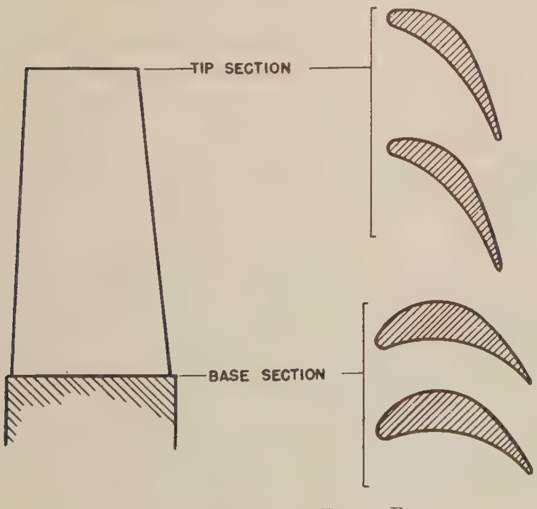


Fig. 13 Typical Moving-Blade Profiles

For ease in manufacture, it is usually desirable that the blade surfaces between the base and tip profiles be in the form of warped conical surfaces generated by a series of straight lines. Such a design greatly simplifies the diemaking problem for forged and cast blades. It is essential when the blades are to be produced by standard machining processes.

The moving blading of a stage designed in accordance with these general procedures is shown in Fig. 14. The stage efficiency determined by test for the element incorporating this particular wheel is approximately 88 per cent at the design conditions. This indicates the general performance level obtainable from such blading.

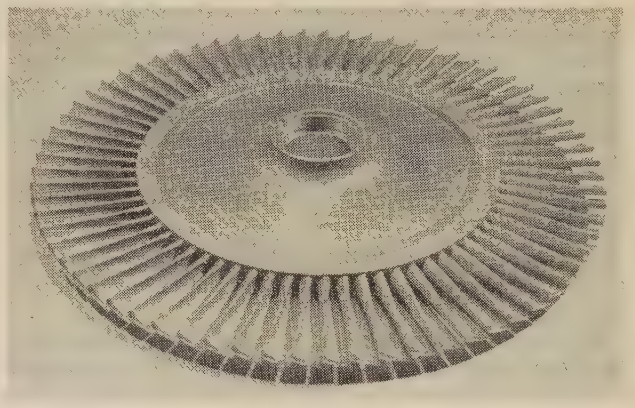


Fig. 14 Bladed Gas-Turbine Disk

## Materials and Design Stresses

*High-Temperature Materials.* There are many considerations which influence the selection of materials for gas-turbine construction. Of necessity, a limited number of criteria must be established to permit direct comparisons of available alloys, and certain properties must be adopted for quantitative use in design calculations.

Allowable working stresses in high-temperature portions of the blade path are based on rupture strength. Adequate 1000-hr stress-rupture data are available for nearly all materials considered applicable to commercial gas-turbine use (8). Consequently, little extrapolation of data is necessary for relatively short-service-life designs. Some uncertainty is generally involved for long-life turbines, but extrapolation is a relatively safe procedure as long as it is limited to approximately one logarithmic time cycle, and ductility can be predicted to remain sufficiently high. Materials which show a tendency toward brittle failure in long-time rupture tests are avoided.

For parts operating at moderate temperatures, the use of yield strength as a design stress criterion has been adopted from steam-turbine practice. Adequate yield strength is essential to prevent harmful deformations due to pure overstressing. Judgment must be exercised, however, since for most alloys yield strength and ductility vary somewhat inversely. Low ductility has been considered acceptable in certain cases, but it is believed that adequate test-bar elongation must be maintained in materials for large thick parts, particularly since uncertainty exists with many alloys regarding changes in ductility over extended periods of time at high temperature.

At the present time, creep-rate and total-deformation data are seldom used for establishing actual working stresses for rotating parts. Stresses which are considered to be permissible from the standpoints of rupture strength and yield strength generally correspond to low values of total deformation. Such deformations are slow and steady in nature and are subject to determination by periodic inspection after a machine has been placed in operation.

Fatigue strength at operating temperature is of considerable importance in selecting blade materials. Accurate fatigue data are not available for many high-temperature alloys, and some materials exhibit no well-defined endurance limit, particularly where conditions conducive to stress corrosion are also present. Compensation for inadequate fatigue data is obtained by keeping bending stresses low and controlling blade vibrational characteristics.

*Selection of Design Stresses.* The present state of knowledge concerning the effects of temperature on metals and the actual temperatures and stresses encountered by parts within a turbine, do not in most cases justify overly complex methods of stress analysis. Discrepancies involved in using simple analyses adequately controlled by experience are less than the errors inherently present due to variations in properties of materials and to unpredictable stresses. These considerations make essential the use of moderate design stresses.

The important principles governing the choice of permissible working stresses are:

1 The machine must be protected against failure due to either fracture or excessive local deformations, under any anticipated load conditions.

2 Protection must be provided against unavoidable variations in properties of the materials as installed. Unwarranted rejections of materials for large machines lead to costly delays in manufacture and shipment.

3 Some margin is essential due to inaccuracies in stress analysis. These inaccuracies result primarily from a lack of complete knowledge of the true stresses existing in many parts. They also arise to some extent from the use of certain simplified stress-analysis procedures which are tolerated only for the purpose of shortening engineering time.

Of the many types of stresses which are encountered in gas-turbine design, average stresses in tension, compression, shear, and bending are most easily determined. Therefore they are used as the guiding criteria. Local high stresses due to stress raisers of various types are taken into account where necessary by stress-concentration factors. In many cases, such stresses are safely relieved by local yielding without failure, as a result of the plasticity of the material at operating temperature. Variable stresses are generally estimated from computed average bending stresses.

The selection of working stress is based on the operating temperature of the part and the specified service life for the turbine. For a given operating temperature, service-life considerations lead to a wide variation in permissible working stress. As a general rule, turbines are classified as short-life units if their expected-life cycle at maximum temperature is less than 10,000 hr, and as long-life units if the corresponding time is 10,000 hr or more.

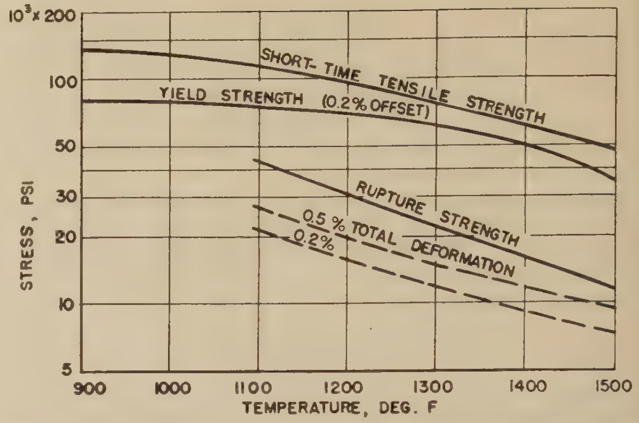


Fig. 15 Materials-Data Curve—Wrought S-590 10,000 Hours

The type of materials-data curve shown in Fig. 15 is used for general gas-turbine design calculations. The practical value of this type of presentation lies in the fact that all parts of a given turbine are normally designed for the same life, but large differences in operating temperature exist between the high and low-pressure ends of the unit. The appropriate working stress for a particular part is determined by applying the selected factors of safety to the material properties at the proper temperature ordinate.

## Stress Analysis

*Blade Stresses.* Blading stress analysis is concerned with a determination of the stresses set up by the centrifugal and bending forces generated by rotation and fluid pressure differences. The highest stresses encountered are almost invariably those resulting from centrifugal forces in the rotating parts. The tensile stress imposed on the base profile of a blade by centrifugal force can be calculated from the following formula

$$s_c = 4.52\gamma f_t A \left(\frac{n}{1000}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots [8]$$

where

$s_c$ = average tensile stress, psi
$\gamma$ = specific weight of blading material, lb per cu in.
$f_t$ = taper factor
$A$ = annular area of blade ring, sq in.
$n$ = rotative speed, rpm

The taper factor is unity for constant-cross-section blades and, assuming constant density of blading material, the stress becomes a function of only annular area and speed. Tapered blades are used where the installation of constant-section blades would result in excessive stresses. The amount of taper permitted in any particular blade is dependent upon the degree to which both flexural strength and efficient blade shape can be maintained. Fig. 16 shows the stress reduction which can be accomplished with various degrees and types of taper.

Basic bending stresses are generated by changes in gas velocity through the blades and by static pressure differences across the blades. Axial and tangential forces per unit length of blade are determined from the estimated flow conditions in the stage. Integration of these forces yields total component loads from which are determined the moments acting on any given profile of the blade.

The maximum stress in a blade is generally at the concave side of the leading edge of the base profile, since the stresses due to centrifugal force and gas bending force are additive in tension at this point. The total tensile stress resulting from centrifugal force and average bending force therefore constitutes the maximum steady stress in the blade. Variable stresses are expressed as percentages of the average bending stresses, and the effects of stress concentration are taken into account. As shown in Fig. 17, the maximum stresses in moving blades are

$$s_s = s_c + s_b \quad \ldots\ldots\ldots\ldots\ldots [9]$$

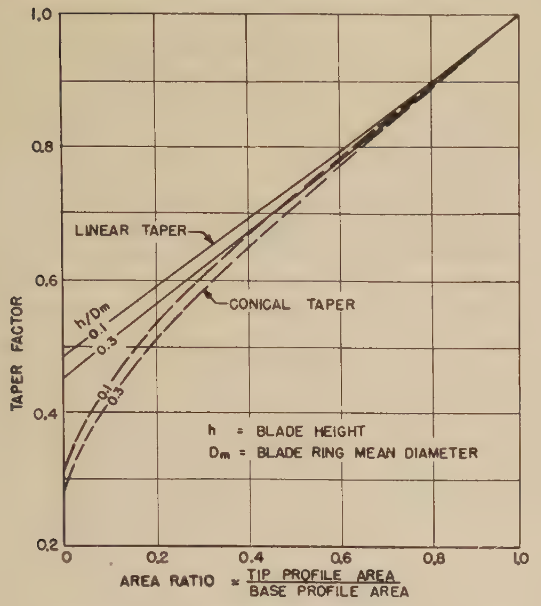


Fig. 16 Variation of Taper Factor With Blade-Profile Area Ratio

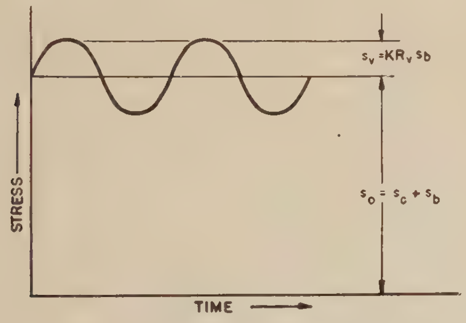


Fig. 17 Assumed Blade-Stress Diagram

$$s_v = KR_v s_b \quad \text{[10]}$$

where

$s_o$ = maximum steady stress, psi
$s_v$ = maximum variable stress, psi
$s_c$ = centrifugal stress, psi
$s_b$ = average bending stress, psi
$K$ = stress concentration factor
$R_v$ = ripple factor

Fillet radii and thickness ratios are such that the stress-concentration factor seldom exceeds 1.5. The ripple factor is a function of the blade pitches, flow conditions, and blade frequency, and it may reach values as high as 0.5 under adverse circumstances. It is somewhat lower with blade frequencies remote from those of possible exciting forces.

Stresses as determined by the foregoing formulas are compared analytically with an assumed failure line on either an endurance limit-yield strength diagram (9) or an endurance limit-rupture strength diagram, as shown in Fig. 18. A minimum factor of safety of 2 is maintained for both comparisons. The actual stresses for use on the rupture-strength diagram are calculated at normal speed, and those for use on the yield-strength diagram are calculated at 120 per cent speed. This overspeed represents the maximum value for which commercial gas turbines are normally designed to withstand harmful permanent deformations.

*Blade-Frequency Analysis.* Accurate control of blade frequency is essential to insure that vibratory stresses do not exceed the limits assumed in stress analysis. Normally, a new blade design is analyzed and suitably modified so that the frequency corresponding to the first mode of transverse vibration lies above the fourth multiple of the maximum rotational speed. This rule has been found to be safe for gas turbines operating from combustion chambers attached by relatively long ducting. If necessary, a safe condition is assured by tuning the actual blading after installation.

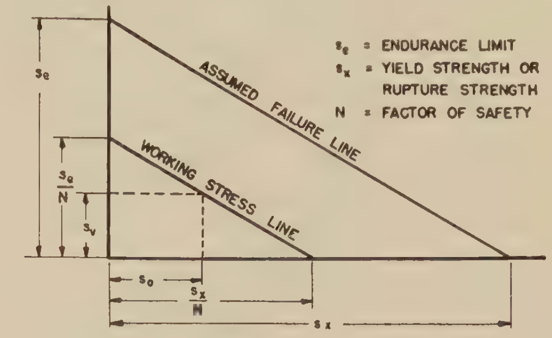


Fig. 18 Assumed Failure Diagram

The frequency of the fundamental mode of vibration of blades in a given ring is expressed by the following formula

$$f_s = 11.0\, C_f \frac{k}{h^2}\sqrt{\frac{E}{\gamma}} \quad \text{[11]}$$

where

$f_s$ = standing frequency, cps
$C_f$ = frequency correction factor
$k$ = radius of gyration of base profile, in.
$h$ = blade length, in.
$E$ = modulus of elasticity, psi.
$\gamma$ = specific weight of material, lb per cu in.

For a value of unity for the frequency correction factor, the formula is identical to that for the frequency of a uniform cantilever beam of equivalent properties. The tie between theory and actual conditions is by means of the frequency correction factor. This factor takes into account blade-taper effects and in addition is dependent upon the actual geometric configuration, the type of blade fixing, and the presence or absence of shrouding and lacing wire.

Moving blades are stiffened to some extent by centrifugal force. The running frequency is calculated from (10)

$$f_r = \sqrt{f_s^2 + B\left(\frac{n}{60}\right)^2} \quad \text{[12]}$$

where

$f_r$ = running frequency at $n$, cps
$B$ = rotation coefficient
$n$ = rotational speed, rpm

The rotation coefficient is dependent upon the degree of blade-root fixing, the geometric shape, and the blade-height ratio. The effect of rotation is generally small, and it can be predicted with practical accuracy for normal constructions from the data in Fig. 19.

Blade vibrational characteristics are best depicted on a frequency diagram similar to that shown in Fig. 20. Safe operating speeds for the turbine may be estimated from such a chart, with allowance for the effects of possible variations in blade frequency.

*Disk Design.* Fig. 21 shows the local elastic-stress distribution in a disk of uniform thickness, when carrying a prescribed rim load at a given rotational speed. The theory and formulation used to determine these stresses are of long standing (11). The stresses are essentially biaxial, consisting of both radial stresses and tangential stresses. The tangential stress at the inner radius of the center-bored disk is considerably above that at the center of the solid disk, which would apparently indicate a much lower safe speed for the former type.

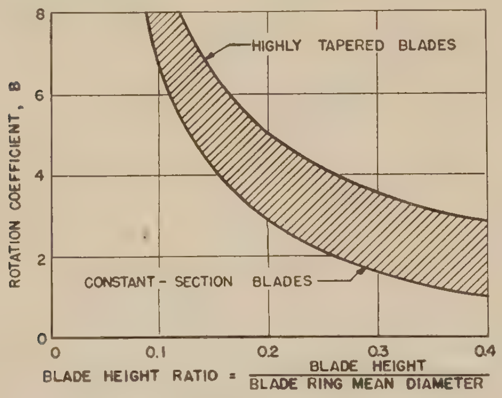


FIG. 19 VARIATION OF ROTATION COEFFICIENT WITH BLADE-HEIGHT RATIO

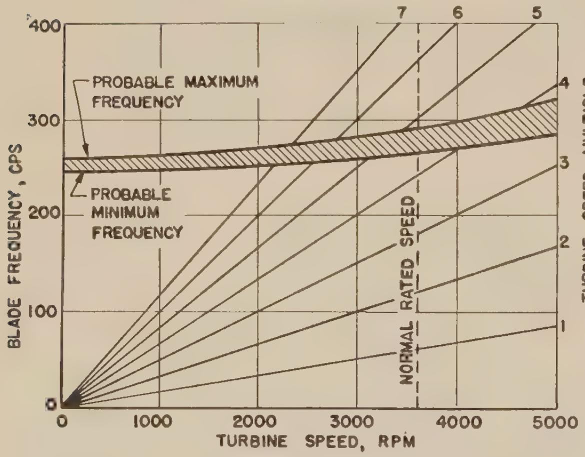


FIG. 20 TYPICAL BLADE-FREQUENCY DIAGRAM

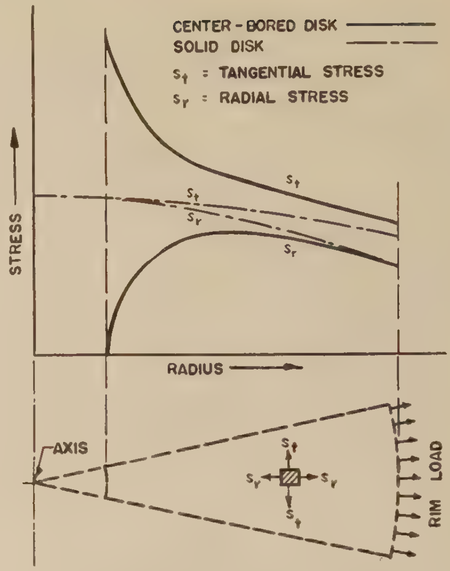


FIG. 21 LOCAL ELASTIC STRESS DISTRIBUTION IN DISK OF UNIFORM THICKNESS

Experimental evidence from a number of sources tends to refute this conclusion (12). The high stress at the inner radius of the center-bored disk is, in effect, a localized stress concentration, which is relieved to a large extent by plastic flow as soon as the elastic limit of the material is exceeded. There is little reduction in load-carrying ability of the disk as a whole.

In practical design, elastic stresses are calculated in detail for blade-carrying elements mainly for the purpose of insuring maximum utilization of the weight of material put into the elements. For comparative purposes, however, the primary criterion is the average tangential stress across the disk radial cross section. This approach assumes, in effect, that the total centrifugal load due to the blades, rim, and disk proper is carried uniformly across the cross-sectional area of the disk. The formula for the average stress is expressed as follows

$$s_{ta} = 28.42\,\gamma\left(\frac{I}{A}\right)\left(\frac{n}{1000}\right)^2 + \frac{P}{2\pi A} \quad \ldots\ldots\ldots [13]$$

where

$s_{ta}$ = average tangential stress, psi
$\gamma$ = specific weight of disk material, lb per cu in.
$I$ = moment of inertia of disk half section about axis of rotation, $\text{in.}^4$
$A$ = area of disk half section, sq in.
$n$ = rotational speed, rpm
$P$ = total centrifugal force due to rim load at speed $n$, lb

Overspeed tests analyzed in accordance with the conception of uniform stress distribution show much closer agreement between average tangential stress and test-bar tensile strength, than when the analysis is based on comparing local elastic stresses and test-bar strength. This is true for both solid and center-bored disks.

Normally, disk stresses as calculated by means of Equation [13] are limited to one half the rupture strength of the material for the specified service life and temperature for the part, when operating at rated speed. Rupture strength becomes of minor importance at moderate temperatures. In such cases, the average tangential stress is limited to one half the yield strength of the material at the specified service temperature, when rotating at 120 per cent of rated speed.

Disk stresses may be reduced considerably if the disk outline is profiled. Calculation of local elastic stresses is helpful in attaining the optimum degree of profiling, and disks are designed with a constant-stress form where possible. In general, thin rims and thick hubs are desirable from the standpoint of over-all stress reduction.

The effects of temperature variation may be of importance in the stressing of disks. These effects are secondary for industrial or utility turbines operating under almost constant load conditions with few start-ups and shutdowns. The temperature gradients during service are small and consistent, and the time intervals for placing the units in or out of service may be made sufficiently long to insure against any deleterious effects.

Stresses generated by thermal gradients may reach serious levels in units subjected to rapid load changes or where quick starting is required. Since these stresses are transient in nature, they induce results similar to fatigue. This phenomenon, which is known as thermal shock, may rapidly lead to failure if not properly taken into account in the design. Without going into particulars, such conditions are best combated by preventing undesirable temperature gradients as much as possible. In this respect, experience up to the present time with artificial cooling of parts subjected to hot gas has been somewhat disappointing. Induced temperature gradients in some cases have led to deformations and failures which would not normally have occurred had the parts been permitted to assume more normal temperature distributions.

### Conclusion

There are many problems in gas-turbine design which cannot be discussed adequately in a presentation such as this. An attempt has been made, however, to show the approaches to some of the more basic problems peculiar to the design of commercial gas-turbine equipment. These approaches are simple and systematic in all cases and they are based primarily upon fundamental theory, modified by experiment and experience.

The gas turbine is in a state of development. This development must be based upon a background of basic data which can be accumulated only through experience. Since the commercial gas turbine is in direct competition with other well-established types of prime movers, the requirements for efficiency, dependability, and low first cost must all be given special consideration. The fulfillment of these requirements is greatly assisted by the organization of fundamental principles and experience into basic design practices similar to those which have been outlined in this paper.

### Acknowledgment

The author desires to express his appreciation to the Allis-Chalmers Manufacturing Company for permission to publish the data contained in this paper. He also wishes to acknowledge the invaluable guidance of Mr. R. C. Allen, during the preparation and review of the various drafts, and the able assistance of Mr. R. W. Rouse in preparing the final manuscript and drawings.

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## Discussion

D. L. Mordell.[3] The writer is disappointed to see that no mention is made of the possibility of using diffusion after the turbine. Rather than regarding the residual kinetic energy as a dead loss, by suitable design some of it may be recovered and used. The effect of any such recovery is simply to increase the effective expansion ratio over the turbine by maintaining subatmospheric pressure at the turbine exhaust annulus. At an exhaust velocity corresponding to Mach number 0.6, the kinetic energy represents 70 deg F or 14 per cent of the total turbine power in a typical simple case. Recovery of one half of this would increase the net or useful output by some 20 per cent. In point of fact, an exhaust Mach number of 0.4 is more probable, and if so, the net gain to be achieved by recovery of one half of the kinetic energy is 10 per cent. In the design shown in Fig. 1 of the paper, space limitations may be severe, but recent aerodynamic developments have indicated how diffusion can be allowed on a bend, if the boundary layer is suitably controlled.

D. G. Traver.[4] A few specific questions have come to mind on which we should like the author to comment. In Fig. 3 of the paper, the impulse-blading efficiency peaks within a point to two of the reaction blading. What are the conditions of this comparison? Our information indicates a somewhat larger difference. However, there are details which influence this consideration. Thus our comparison would be at the same Reynolds number and aspect ratio (ratio of blade length to axial width), and our Mach number would be sufficiently below 1 not to influence this comparison. In general, the author's curve substantiates ours in that we believe an impulse stage can be made which performs almost as well as a reaction stage. Frequently the mechanical advantages of the impulse stage counterbalance this small sacrifice in efficiency.

The popular classification of turbines into pure impulse and pure reaction types has almost lost its meaning to the gas-turbine designer, for he often deals with large-diameter-ratio blading in which three-dimensional effects are large, and in which there may be a radial variation in degree of reaction. Gas-turbine designers often depart from impulse or reaction conditions at the mean diameter even for small diameter ratios, for they may find a partial reaction stage better suited to their design requirements. There is no real justification for designing to the arbitrary limits of reaction or impulse stages, and it must be assumed that some sort of continuous efficiency envelope between these two types exists. Would the author indicate what form this envelope might take, and what he considers a "typical" impulse stage?

Referring to Fig. 7 of the paper, we use aspect ratio as a design parameter, and we would be interested in knowing the aspect ratios of these two curves. Our data for aspect ratio of 3 and Reynolds number = 100,000 (based on the throat hydraulic diameter as characteristic length) are the average of the author's curves over the entire range. Does Fig. 7 apply equally to impulse and reaction blading?

In Fig. 12 our findings are identical to the author's in the range of opening coefficients which we normally use in turbine design.

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[4] Research Engineer, Analytical Section, Elliott Company, Jeannette, Pa.

In regard to the author's discussion of aerodynamic loading and optimum pitch as developed by Zweifel, we use a variable optimum load coefficient that varies linearly with the reciprocal of aspect ratio, because the theory is developed for two-dimensional (infinite aspect ratio) flow conditions only. Our test data verify this variable load coefficient for normal reaction blading. However, our data do not agree, even in the two-dimensional case, with the optimum spacing indicated for impulse blades, but indicate a larger optimum pitch than calculated by Zweifel. This can be rationalized by assuming a more realistic ideal pressure distribution for impulse blades than the rectangular one assumed by Zweifel.

### AUTHOR'S CLOSURE

Mr. Mordell points out the possibility of using diffusion to recover a portion of the residual kinetic energy from turbine-exhaust blading. The practicability of reducing leaving loss by this method is dependent upon the amount of kinetic energy available for recovery and upon space requirements for efficient diffusion. In multistage turbines of the general type shown in Fig. 1, the axial velocity of the gas leaving the last row of blades seldom exceeds 400 fps at rated load. Recovery of 50 per cent of the energy corresponding to this velocity would improve power-element efficiency about one per cent. However, power-element length would have to be increased over 25 per cent to provide an efficient diffusing turn for the exhaust gas. An increase in length of this magnitude is not practical for many installations, particularly for locomotive and marine service, in view of the small resultant gain in over-all efficiency.

With reference to Mr. Traver's questions concerning Fig. 3, the title is misleading in that the word "typical" applies to the curves rather than to the blading. Instead of identifying the stages as "reaction" and "impulse," it would be more proper to refer to them as "symmetrical" and "unsymmetrical." In both cases Reynolds number and aspect ratio are sufficiently high that their influences are small. The impulse or unsymmetrical staging has warped moving blades with a stage reaction at design conditions of zero at the root diameter and about 25 per cent at the mean diameter. The blading efficiency is somewhat better than that of a more conventional stage. The reaction or symmetrical blading is designed for 50 per cent reaction at all radii.

We have insufficient experimental evidence to plot, as suggested by Mr. Traver, a continuous efficiency envelope for blading varying in stage reaction from zero to 0.50. The shape of such a curve can be deduced to a certain extent from the following experimental results:

1 The efficiency of normal reaction blading is not affected by small unbalances in stage reaction above or below 0.50. The slope of the efficiency envelope curve must therefore be essentially zero at a stage reaction of 0.50.

2 The efficiency of a nominal impulse stage is generally improved by the introduction of a small amount of reaction, provided reasonable control over blade clearances is maintained to prevent gas leakage. The slope of the efficiency envelope curve must therefore be slightly positive for a stage reaction of zero.

We can probably assume from the foregoing that the efficiency envelope curve is roughly parabolic in form with a peak at a stage reaction of 0.50. However, the curve would be of academic interest only, as the internal configuration of any specific stage as regards blade height, diameter ratio, profile form, and operating clearance always exerts a major influence on its general efficiency level.

Concerning Mr. Traver's questions on Fig. 7, which shows expansion energy coefficient curves used in performance analysis, these data are assumed to apply to two-dimensional flow when the Reynolds number based upon throat-opening hydraulic diameter is 100,000 and higher. A value of 100,000 represents the lower limit of normal design practice, and over-all turbine tests seem to indicate only minor changes in efficiency as operating conditions are varied a moderate amount from this level.

Since the data in Fig. 7 apply only to two-dimensional flow, a gross stage power output calculated using these coefficients must be corrected for three-dimensional effects. The correction is made in terms of an end loss which includes clearance leakage, interference effects, and other secondary flow losses. The magnitude of the end loss is estimated from the blade height, blade profile, operating clearance, and clearance configuration. An aspect ratio such as defined by Mr. Traver (ratio of blade length to axial width) is not used as a design parameter.

The energy coefficients shown in Fig. 7 were determined by analyses of over-all turbine tests, and the curves may be considered to represent statistical averages. Individual tests show moderate variations above and below the curve values. The fact that wide blades generally show improved efficiency (provided the blades are of reasonable length) is believed to be due to two influences:

1 In practice it is seldom possible to maintain exact geometric similarity between wide and narrow blades. Trailing edge-wake loss generally increases as blading is narrowed, with a consequent slow decrease in over-all blade-energy coefficient.

2 Reynolds number effects have not been isolated satisfactorily in over-all turbine tests, but undoubtedly they are responsible for some reduced efficiency in narrow blades at moderate Reynolds number levels.

The data in Fig. 7 apply in general to both impulse and reaction blades. The expansion-energy coefficient of reaction blades or nozzles with very small outlet angles may fall slightly below the level of the curves. The kinetic-energy coefficient of impulse blades with very low deflection angles is generally somewhat higher than the expansion-energy coefficient as determined from Fig. 7. However, these types of elements are not normally employed in gas-turbine blade paths, so that the general accuracy of Fig. 7 is not affected for practical application.

# Bending of an Ideal Plastic Metal[1]

By J. D. LUBAHN[2] and G. SACHS[3]

**The stresses and strains in plastically bent parts have been analyzed for the two limiting conditions of (*a*) a very wide plate (plane strain), and (*b*) a very narrow bar (plane stress). The complete solution is presented for a hypothetical metal with no strain-hardening, and the method is described for treating any actual metal. The solution was obtained by a method of successive approximations, each approximation employing various graphical processes. The gradual change in cross-sectional contour with progressive bending was obtained by considering small successive intervals of increasing curvature. The final solution shows the movement of the neutral axis toward the compression surface, the decrease in the radial dimension of the part, and the gradual divergence between the tangential strains at the inside and outside surfaces. The solutions for plane stress and plane strain were nearly identical as regards the tangential strains and the changes in the radial dimension. Experimental measurements of surface strains and cross-sectional contour of bends conformed well with the results of the calculations.**

## Nomenclature

The following nomenclature is used in the paper:

$A$ = angle subtended by a portion of the bend
$a$ = radius to concave surface of bent part
$a$ as a subscript refers to concave surface of bent part
$b$ = radius to convex surface of bent part
$b$ as a subscript refers to convex surface of bent part
$e$ = conventional strain
$F$ = component of force acting on an element of volume
$f$ as a subscript denotes final (strained) condition
$h$ = height or dimension in radial direction
$k$ = flow stress, i.e., uniaxial stress necessary to cause plastic flow
$L$ = element of length (tangential unless otherwise specified)
$m$ as a subscript denotes center (with respect to curvature, i.e., $h_0/a$) of a finite interval of bending
$n$ as a subscript denotes neutral axis, i.e., point of zero tangential stress or zero tangential strain differential
$r$ = radius to an arbitrary point
$r$ as a subscript denotes radial direction
$s$ = stress
$t$ as a subscript denotes tangential direction (will be omitted where no ambiguity arises)
$V$ = volume
$w$ = breadth [$= w_0(1 + e_w)$].
$w$ as a subscript denotes lateral direction
$x$ = distance from an element of volume to concave surface ($= r - a$)
0 as a subscript denotes initial (unstrained) condition
1 as a subscript denotes direction of largest principal strain or stress
2 as a subscript denotes direction of intermediate principal strain or stress
3 as a subscript denotes direction of smallest principal strain or stress
$\epsilon$ = natural strain [$= \ln(1 + e)$]
$\bar{\epsilon}$ = uniaxial tensile strain causing an equivalent strain-hardening (when flow stress is a function of three principal strains)
$'$ = beginning of finite interval of bending
$''$ = end of finite interval of bending

## Introduction

The bending of metal bars and plates by amounts sufficient to cause plastic deformation of practically the entire volume of the metal causes a condition of stress and strain throughout the part which is exceedingly complex. Under certain conditions, however, it is possible to treat the problem quantitatively, as discussed later, although the solution is involved and tedious. The simplifying conditions which are necessary to allow mathematical treatment of the problem are as follows: (*a*) It must be considered that the part is externally loaded only by end moments, i.e., that there is no pressure against the concave or convex surface, except at the ends of the bent portion; (*b*) the region of elastically deformed metal must be negligibly small; (*c*) all elements of volume of the part must have either zero lateral[4] stress (condition of plane stress) or zero lateral strain (condition of plane strain); and (*d*) the bend must be long enough in the circumferential direction so that the end effects do not disturb the behavior of the metal near the center of the bend. These circumstances will be approached rather closely in bars which are sufficiently wide (approaching plane strain) or sufficiently narrow (approaching plane stress) and which contain a bend that is neither too mild nor too sharp.

Previous treatments (1, 2, 3, 4)[5] of plastic bending have dealt with an even simpler set of circumstances where only the stresses and strains in the circumferential direction have been considered, the changes in cross-sectional contour have been neglected, and the effects of curvature on the position of the neutral axis have been disregarded.

In the present paper an "ideal plastic metal," i.e., one exhibiting no strain-hardening, will be assumed. Even with this assumption, however, the solution of the plastic-bending problem requires graphical methods for determining both the stresses and strains in a narrow bar and for determining the strains in a wide plate; only the stresses in a wide plate are obtainable algebraically. Consequently, for an actual metal with a specific stress-strain curve, the solutions would be but little more complex,

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[1] This paper originated in an investigation conducted at Case Institute of Technology, Cleveland, Ohio, under contract with the National Defense Research Committee of the Office of Scientific Research and Development. The completion of the analytical work reported in this paper and further experimental work were made possible by the Frederick Cottrell grant made by the Research Corporation, New York, N. Y. A preliminary report on the experimental work is in preparation.

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Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Paper No. 48—A-168.

[4] See Fig. 1 for definition of directions.

[5] Numbers in parentheses refer to the Bibliography at the end of the paper.

as will be shown. On the other hand, the solutions for the ideal plastic metal conform closely to the deformation characteristics of real metals, so it appears that little is to be gained by repeating the procedure to be given for any real metals. This statement does not apply to the stresses, however, and consequently the bending loads, springback characteristics, and other aspects of bending require consideration of the strain-hardening and cannot be deduced accurately from the results of the present analysis.

### Plastic-Flow Laws and Conditions of the Problems

In the following solutions of plastic-bending problems, the behavior of the metal will be considered to be governed by the following empirical relations,[6] which are generally accepted as the "laws" of plastic flow:

(*a*) The condition that the volume remains constant during plastic flow can be expressed in terms of the principal natural strains by

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0 \qquad [1a]$$

$$d\epsilon_1 + d\epsilon_2 + d\epsilon_3 = 0 \qquad [1b]$$

where the natural strain $\epsilon$, is defined in terms of the conventional strain $e$, or change in length divided by initial length, by

$$\epsilon = \ln(1 + e)$$

(*b*) The condition of stress under which plastic flow proceeds is given by the energy-of-distortion condition

$$(s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_1 - s_3)^2 = 2k^2 \qquad [2]$$

In this equation, $k$ is the uniaxial stress necessary to cause plastic flow.

(*c*) The relation between the strains and stresses in the plastic state is given by

$$\frac{s_1 - s_2}{d\epsilon_1 - d\epsilon_2} = \frac{s_2 - s_3}{d\epsilon_2 - d\epsilon_3} = \frac{s_1 - s_3}{d\epsilon_1 - d\epsilon_3} \qquad [3]$$

In addition to the foregoing relations governing the behavior of the metal itself, certain general principles of mechanics also apply to the situation at hand.

(*d*) For a stationary body, the equilibrium-of-force condition requires that the sum of the force components in any given direction (in particular, the radial direction) must be zero

$$\Sigma F_r = 0 \qquad [4]$$

(*e*) For loading by end moments only, i.e., no external radial forces in the region considered, the equilibrium-of-force condition applied at the concave and convex surfaces of the bent part requires that the radial stresses at these surfaces be zero

$$s_r = 0 \text{ when } r = a \qquad [5a]$$

$$s_r = 0 \text{ when } r = b \qquad [5b]$$

### Solution for Plane Strain

*General Considerations.* In the case of plane strain, the distribution of the stresses between initially unknown positions of the boundary surfaces can be determined algebraically. Subsequently, the position of the neutral axis can be determined, from which it is possible to calculate the strains and the height (see Fig. 1), and thus the positions of the concave and convex surfaces of the bent part.

If a wide plate is bent, the circumferential stretching at the convex surface tends to cause lateral contraction of this surface, and similarly there is a tendency for the concave surface to expand laterally. This would cause lateral curvature of the part; but the resistance of the circumferentially curved plate prevents such lateral bending almost completely, and the lateral strains are therefore the same throughout the volume of the bend. Furthermore, the lateral resistance of the flat portions adjacent to the bend prevents any average lateral extension or contraction of the bend, so that the lateral strain $\epsilon_w$, is practically zero at every point.

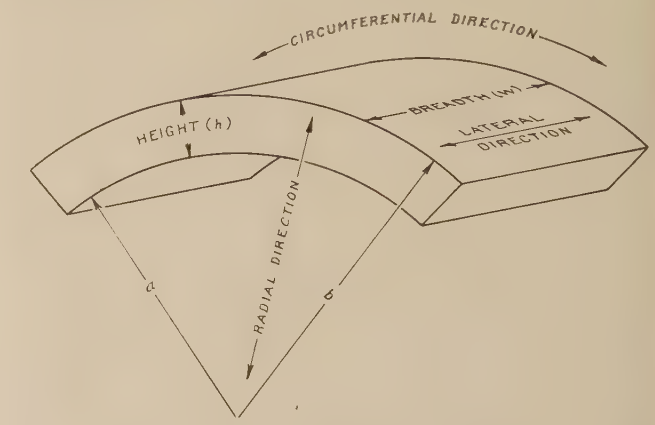

Fig. 1 Definitions of Directions and Dimensions in Bent Part

From considerations of symmetry it can be seen that the shear stresses are zero on planes determined by the radial, lateral, and circumferential directions, and consequently these are the principal directions. Because of the constant volume condition, the value zero for the lateral strain will require this to be the intermediate principal strain $\epsilon_2$, and the intermediate principal stress will be the lateral stress. Applying $\epsilon_2 = 0$ to Equations [3] and [1*b*] yields

$$s_2 = \frac{s_1 + s_3}{2} \qquad [6]$$

Then Equation [2] becomes

$$s_1 - s_3 = \frac{2k}{\sqrt{3}} \qquad [7]$$

*Stress Distribution for Plane Strain.* For rotational symmetry, equilibrium of force in the radial direction Equation [4] yields the following differential equation relating the radial and tangential stresses (5)

$$\frac{ds_r}{dr} = \frac{s_t - s_r}{r} \qquad [8]$$

At the convex surface, $s_t$ is a tensile stress and $s_r$ is zero, so that $s_t$ is the largest and $s_r$ is the smallest principal stress. Then Equation [7] becomes

$$s_t - s_r = \frac{2k}{\sqrt{3}} \qquad [9]$$

Combining this with Equation [8] and rearranging yields

$$\frac{ds_r}{k} = \frac{2dr}{r\sqrt{3}}$$

Integrating between the boundary condition [5*b*] and an arbitrary point $r$, $s_r$

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[6] For a detailed discussion of these relations, see Nadai (1).

$$\frac{s_r}{k} = \frac{2}{\sqrt{3}} \ln \frac{r}{b} \qquad [10]$$

Equation [10] shows that $s_r$ becomes negative as $r$ becomes smaller than $b$ and consequently, as $r$ deviates from $b$, Equation [10] is applicable as long as $s_t$ and $s_r$ are continuous.

At the concave surface, $s_t$ is a compressive stress and $s_r$ is zero, so that $s_r$ is the largest and $s_t$ the smallest principal stress. Then Equation [7] becomes

$$s_r - s_t = \frac{2k}{\sqrt{3}} \qquad [11]$$

which, combined with Equation [8] and integrating between the boundary Condition [5a] and an arbitrary point, $r$, $s_r$ becomes

$$\frac{s_r}{k} = -\frac{2}{\sqrt{3}} \ln \frac{r}{a} \qquad [12]$$

According to Equation [12], $s_r$ becomes negative, as $r$ becomes greater than $a$, and consequently, as $r$ deviates from $a$, Equation [12] is applicable as long as $s_r$ and $s_t$ are continuous.

The solutions Equations [10] and [12] for $s_r$ will be identical at one and only one value of the radius, so that Equation [10] will apply at larger radii and Equation [12] at smaller radii. Consequently this is the point where the tangential stress changes from positive[7] to negative, and it will be designated as the neutral axis, $r_n$. The position of the neutral axis is obtained by setting equal to each other the two expressions Equations [10] and [12] for $s_r$, yielding

$$r_n = \sqrt{ab} \qquad [13]$$

The distributions of radial stress in bends of various curvatures are shown in Fig. 2, in terms of the as yet unknown height, $h$. These curves show clearly the increase in radial compression as the curvature increases. The distribution of tangential and lateral stresses, as well as the radial stress, are shown in Fig. 3 for one particular value of the curvature of the bar, namely, for $h/a = 1$.[8]

*The Neutral Axis.* When $r < r_n$, the tangential stress is the smallest principal stress, as discussed previously, and consequently the principal direction in which the algebraically smallest change, $d\epsilon$, in strain occurs is the tangential direction, i.e., $d\epsilon_t = d\epsilon_3$. Since $d\epsilon_2 = 0$ and considering Equation [1b], $d\epsilon_3$ must be negative. Thus $d\epsilon_t$ is also negative for $r < r_n$. Likewise, $d\epsilon_t$ is positive when $r > r_n$ because the tangential stress is the largest principal stress in this region. Consequently, $d\epsilon_t$ is zero at the neutral axis; and the neutral axis may be defined not only as the point of zero tangential stress, but also as the point of zero tangential strain differential. The variation with curvature of the neutral axis with respect to the as yet unknown positions of the bounding surfaces ($r = a$ and $r = b$) is shown in Fig. 4. The fact that $d\epsilon_t = 0$ when $r_n = \sqrt{ab}$, together with the value of the curvature and the condition that the distribution of (conventional) tangential strain is linear across the radius,[9] constitute the necessary information for determining the radial distribution of tangential strains.

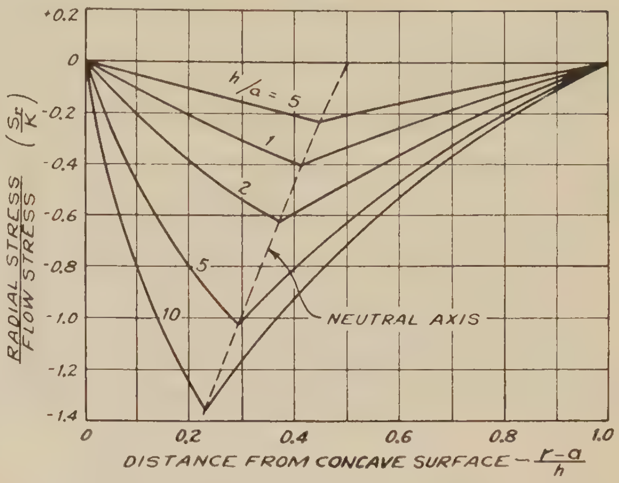

Fig. 2 Distribution of Radial Stress in Bends of Various Curvatures for Plane Strain

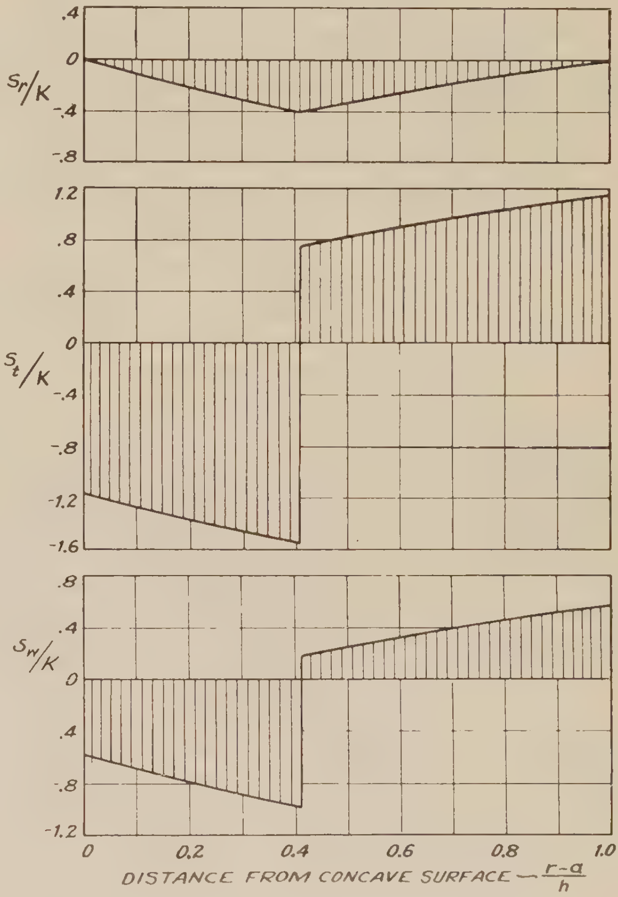

Fig. 3 Radial, Tangential, and Lateral Stresses for Plane Strain for $h/a = 1$

*Strain Distribution.* Because of the continuously changing position of the neutral axis with increasing curvature (see Fig. 4), the total tangential strain must be determined by integrating the differentials of strain occurring during small increments of bending in which the height remains constant and the neutral axis remains at a fixed distance ($r_n - a$) from the concave surface and the length $L_n$, remains fixed, Fig. 5. Two cross sections bounding an initial length of the bar (before bending) of $L_0$ will subtend an

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[7] For very large curvatures (small radii ($a/h_0$) of curvature, $s_t$ according to Equations [9] and [10] may be negative at $r = r_n$, but the magnitude of the discontinuity in $s_t$ at $r_n$ will still be $4k/\sqrt{3}$ (compare [9] and [11]).

[8] It is interesting to note that the stress distribution in a plastically bent plate is identical with that which would be obtained if one thick-walled tube were shrunk onto another in such a manner that both were in a condition of complete plastic flow (6).

[9] It can be shown experimentally that the radial distribution of tangential strains is linear near the (tangential) center of even a rather sharp bend.

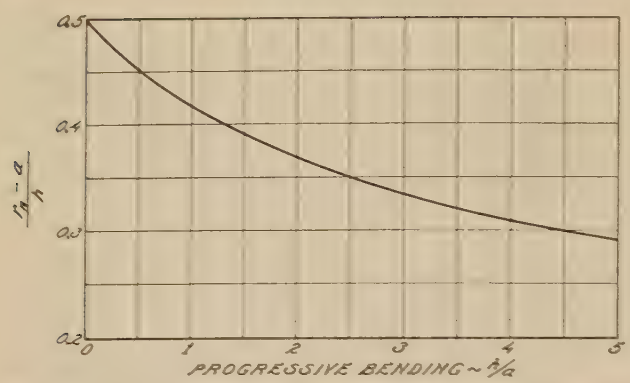

Fig. 4 Change in Position of Neutral Axis During Bending for Plane Strain

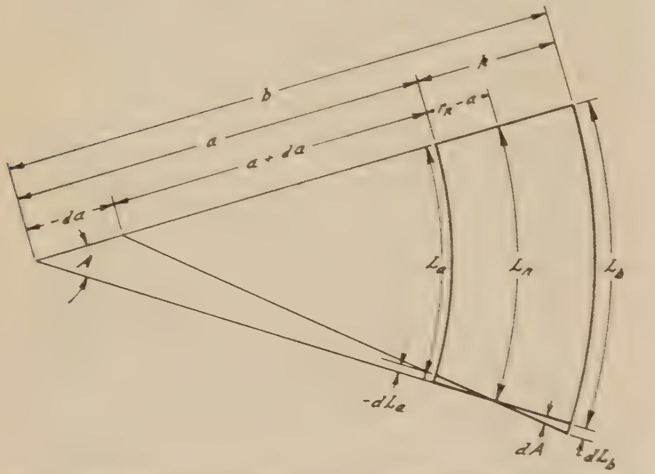

Fig. 5 Geometrical Changes During an Infinitesimal Interval of Bending

angle, $A$, during the interval, and may be considered as rotating about the ends of the neutral axis during the interval. If the radius $a$, to the concave surface changes by $da$ during the interval, the cross section at one end of the neutral axis will rotate through an angle $dA$, with respect to the cross section at the other end of the neutral axis, Fig. 5. The lengths, $L_a$ and $L_b$ of the fibers at the concave and convex surfaces, respectively, will change by small amounts, $dL_a$ and $dL_b$, respectively. Fig. 5 yields two equations each for the lengths $L_b$ and $L_a$, of the surface fibers

$$L_a = Aa \quad L_b = Ab = A(a + h) \qquad [14]$$

and

$$dL_a = (a - r_n)dA = \left[a - \sqrt{a(a + h)}\right] dA \qquad [15]$$

$$dL_b = (a + h - r_n)dA = \left[a + h - \sqrt{a(a + h)}\right] dA \qquad [16]$$

The constant volume condition, Fig. 6, yields the relation

$$\frac{h(L_a + L_b)}{2} = h_0L_0 \qquad [17]$$

Since by definition

$$1 + e_a = \frac{L_a}{L_0} \qquad 1 + e_b = \frac{L_b}{L_0} \qquad [18]$$

Equation [17] reduces to

$$\frac{h_0}{h} = 1 + \frac{1}{2}(e_a + e_b) \qquad [19]$$

In order to determine the surface strains ($e_a$ and $e_b$) after a change in curvature from zero to $h/a$, a method of successive approximations has been used consisting of the following steps:

1*a* Obtain a first approximation to the strains by assuming that the height remains constant and integrating Equations [15] and [16] algebraically.

1*b* Obtain a first approximation to $h$ by using Equation [19] and the results of step 1*a*.

2*a* Using the values of $h$ found by step 1*b*, integrate Equations [15] and [16] graphically to obtain a second approximation to the surface strains.

2*b* Determine a second approximation to $h$ using Equation [19] and the results of step 2*a*.

The foregoing procedure yields successive approximations to the correct solution, each of which is more nearly correct than the preceding one. Consequently the procedure described under steps 2*a* and 2*b* may be repeated until the desired accuracy is obtained.

*Step* 1*a*. Considering $h$ constant and differentiating Equation [14]

$$dL_a = adA + Ada$$

$$dL_b = dA(a + h) + Ada$$

By means of these relations and Equation [14], $A$ can be eliminated from Equations [15] and [16], yielding

$$\frac{dL_a}{L_a} = \frac{da}{a} - \frac{da}{\sqrt{a(a + h)}} \qquad [20]$$

$$\frac{dL_b}{L_b} = \frac{da}{a + h} - \frac{da}{\sqrt{a(a + h)}} \qquad [21]$$

These equations can be integrated between the limits $L_a = L_b = L_0$ when $a = \infty$, and the general condition of strain, yielding

$$\frac{L_a}{L_0} = 1 + e_a = \frac{4a}{2a + h + 2\sqrt{a(a + h)}} \qquad [22]$$

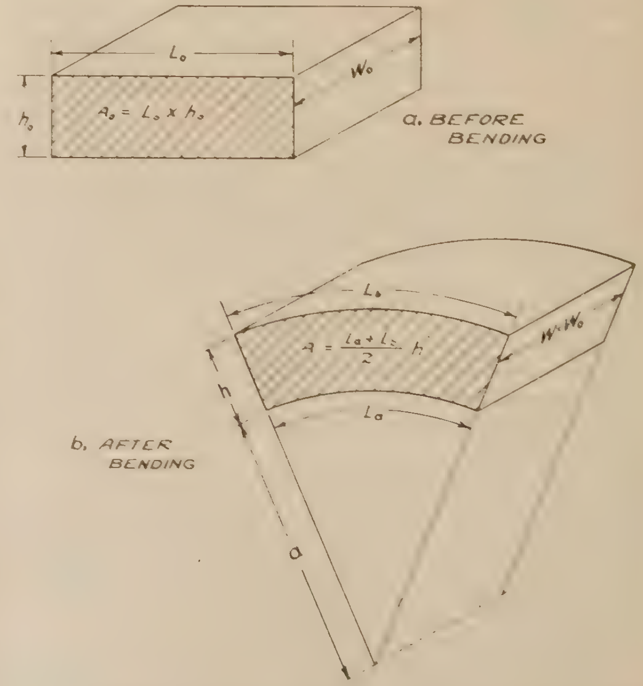

Fig. 6 Constant Volume Condition for Portion of Bent Sheet

$$\frac{L_b}{L_0} = 1 + e_b = \frac{4(a + h)}{2a + h + 2\sqrt{a(a + h)}} \ldots\ldots [23]$$

These values of $e_a$ and $e_b$ are shown in Fig. 7, curve 1 (to designate the first approximation).

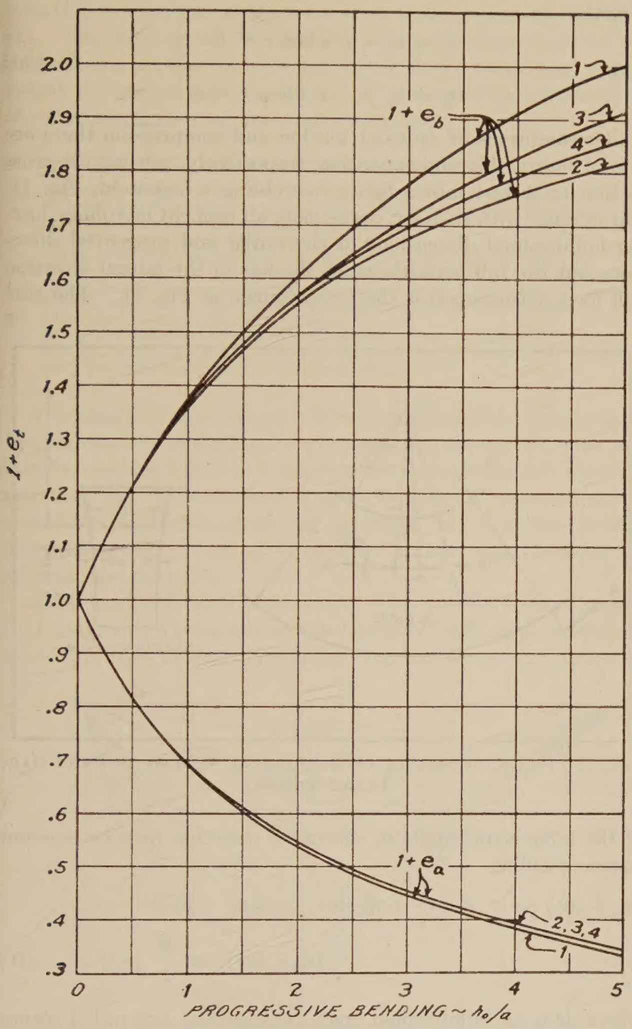

FIG. 7 SUCCESSIVE APPROXIMATIONS TO EXTREME TANGENTIAL STRAINS FOR PLANE STRAIN

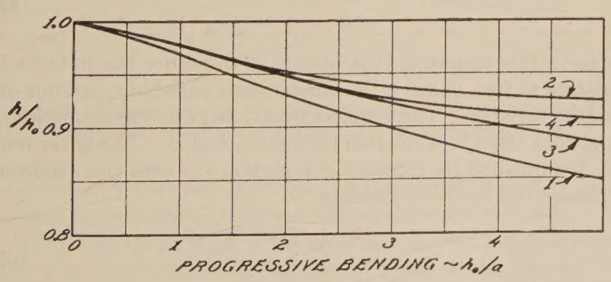

FIG. 8 SUCCESSIVE APPROXIMATIONS TO CHANGE IN HEIGHT ON BENDING FOR PLANE STRAIN

*Step* 1*b*. Using the surface strains given by Equations [22] and [23], the height (expressed as a fraction of the initial height) can be determined from Equation [19]. This is plotted in Fig. 8, curve 1 (to designate the first approximation).

*Step* 2*a*. For graphical integration of Equations [15] and [16], these equations may be applied to a small finite interval of bending whose beginning is designated by prime, and whose end is designated by double prime. If the interval is sufficiently small, $h$ and $(r_n - a)$ may be considered as constant during the interval and may be taken at a curvature midway (subscript $m$) between that at the beginning and that at the end of the interval. Then Equations [15] and [16] become

$$L''_a - L'_a = (A'' - A')\,(a_m - r_{nm}) \ldots\ldots\ldots\ldots [24]$$

$$L''_b - L'_b = (A'' - A')\,(a_m + h_m - r_{nm}) \ldots\ldots [25]$$

where

$$r_{nm} = \sqrt{a_m(a_m + h_m)}$$

Applying Equation [14] to the beginning and end of the interval yields values of $A'$ and $A''$ which can be substituted into Equations [24] and [25] yielding

$$\frac{L''_a}{L'_a} = \left(\frac{a''}{a'}\right) \frac{a' - a_m + r_{nm}}{a'' - a_m + r_{nm}} \ldots\ldots\ldots\ldots\ldots\ldots [26]$$

$$\frac{L''_b}{L'_b} = \left(\frac{a'' + h''}{a' + h'}\right) \left(\frac{a' - a_m + r_{nm}}{a'' - a_m + r_{nm}}\right) \ldots\ldots [27]$$

Dividing numerator and denominator of the left member by $L_0$ and of the right member by $h_0$ yields the strains at the end of the interval in terms of the strains at the beginning of the interval and quantities available from the previous approximation

$$\left(\frac{L''_a/L_0}{L'_a/L_0}\right) = \frac{1 + e''_a}{1 + e'_a} = \left(\frac{a''/h_0}{a'/h_0}\right)\left(\frac{a'/h_0 - a_m/h_0 + r_{nm}/h_0}{a''/h_0 - a_m/h_0 + r_{nm}/h_0}\right) \ldots\ldots\ldots [28]$$

$$\left(\frac{L''_b/L_0}{L'_b/L_0}\right) = \frac{1 + e''_b}{1 + e'_b} = \left(\frac{a''/h_0 + h''/h_0}{a'/h_0 + h'/h_0}\right) \times \left(\frac{a'/h_0 - a_m/h_0 + r_{nm}/h_0}{a''/h_0 - a_m/h_0 + r_{nm}/h_0}\right) \ldots\ldots\ldots [29]$$

Values of $h/h_0$ at $a'/h_0$, $a_m/h_0$, and $a''/h_0$, respectively, are given in Fig. 8, curve 1. The fact that intervals of $h_0/a$ of one half are sufficiently small to give good accuracy can be shown by comparing the results of Equations [28] and [29] for this interval size and for a constant value of $h$, $(h = h_0)$, with the results of Equations [22] and [23], respectively. The second approximation to the surface strains obtained by Equations [28] and [29] is shown in Fig. 7, curve 2.

*Step* 2*b*. Using the surface strains given in Fig. 7, curve 2, a second approximation to the height can be determined from Equation [19]. This is shown in Fig. 8, curve 2.

The third and fourth approximations (curves 3 and 4 in Figs. 7 and 8) show that consecutive solutions yield values approximately midway between those of the two preceding solutions. This information makes it possible to make an estimate directly of the final solution, which may be verified by applying steps 2*a* and 2*b* of the foregoing procedure to the estimate. The result, Fig. 9, shows that the estimate based upon four approximations is quite accurate.

The final solution for the surface strains is shown in Fig. 10 where the results are compared with the "conventional bending strains," i.e., those obtained by assuming constant height and that the neutral axis remains at the center of the height.

As will be shown, the tangential surface strains are the same for plane stress as for plane strain (within the limits of accuracy of the method); and in Fig. 10 are presented some data for various conditions between these limits, which show that the theoretical solutions agree closely with experimental measurements for bars or plates of any width. Of particular significance is the fact that

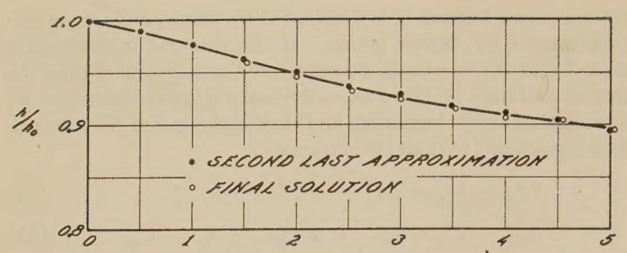

Fig. 9 Height Change During Bending for Plane Strain According to Last Approximation and Final Solution

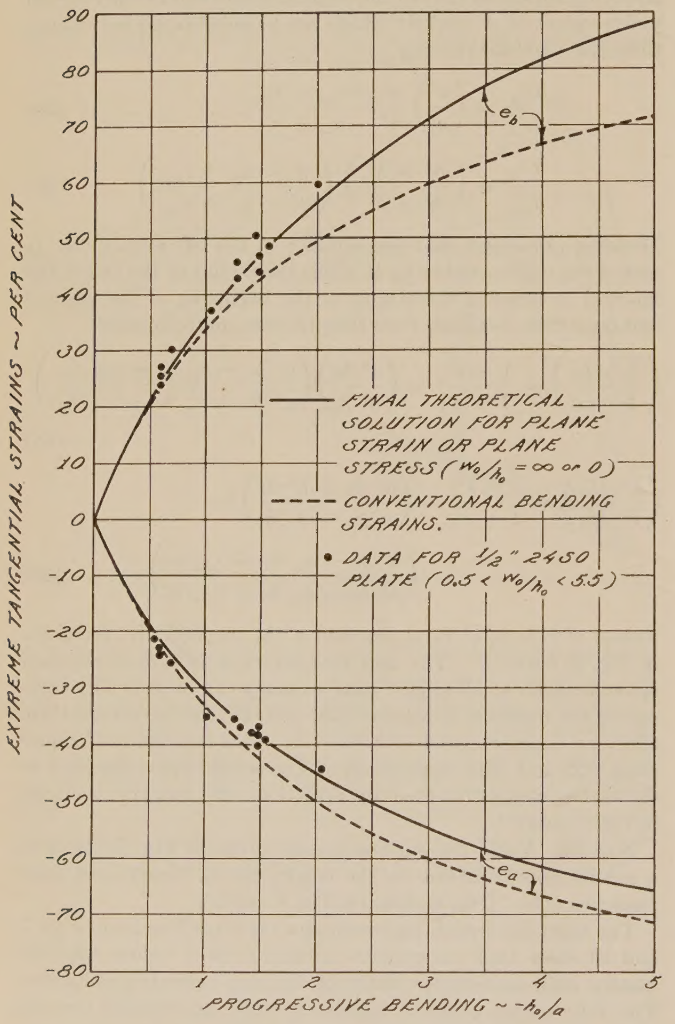

Fig. 10 Comparison of Measured and Theoretical Circumferential Surface Strains for Wide Range of $W_0/h_0$ Values Between Plane Strain and Plane Stress

the agreement is good between the theoretical solution for an ideal plastic metal and data for an actual metal. This means that the strain-hardening characteristics of the metal have but little influence on the strains in bending and consequently the foregoing solution should be applicable to a wide variety of metals, in so far as the strains are concerned. However, the stresses will vary considerably from metal to metal.

## Solution for Plane Stress

*Development of Equations for the Stresses.* A sufficiently thin strip which is bent edgewise, Fig. 11, will have zero stress in the lateral direction (i.e., $s_w = 0$), and thus will be in a state of "plane stress." Since the radial stress is zero at the convex and concave surfaces, these surface fibers will be in a state of uniaxial tension and uniaxial compression, respectively, in the tangential direction, i.e.

$$\left.\begin{aligned} s_t &= s_1 = k \text{ when } r = b \\ \text{and} \qquad s_t &= s_3 = -k \text{ when } r = a \end{aligned}\right\} \qquad [30]$$

Under conditions of uniaxial tension and compression there are lateral contraction and expansion, respectively, causing the cross section to distort into a figure resembling a trapezoid, Fig. 11. Out of a bar with such a cross section, an element of volume having infinitesimal dimensions in the radial and tangential directions but the full breadth, $w$, of the bar in the lateral direction will have acting upon it the forces shown in Fig. 11. The sum

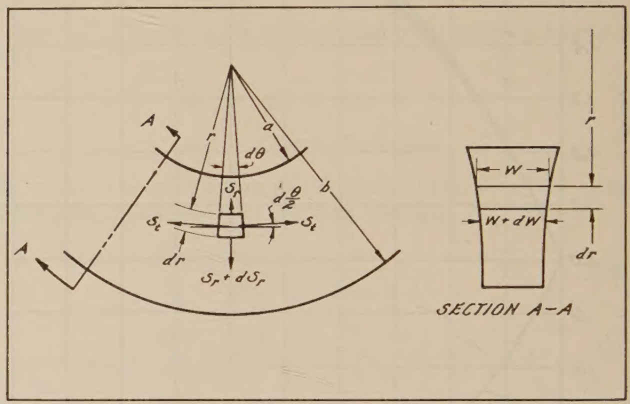

Fig. 11 Force Acting on an Element of Volume in Bent Bar; Plane Stress

of the force components in the radial direction may be equated to zero, yielding

$$(s_r + ds_r)(w + dw)(r + dr)d\theta - s_r w r d\theta - 2 s_t dr (w + dw) \sin\frac{d\theta}{2} = 0 \quad [31]$$

where $d\theta$ is an infinitesimal angle between the two radial planes which bound the element. Equation [31] reduces to

$$\frac{ds_r}{d_r} = \frac{s_t - s_r}{r} - \frac{s_r dw}{w dr} = \frac{s_t - s_r}{r} - \frac{s_r de_w}{(1 + e_w)dr} \quad [32]$$

To solve this equation, it is necessary to reduce the number of variables to two, namely, the independent variable $r$, and one dependent variable. This requires that $e_w$ be known as a function of $r$ and that there be a relation between $s_t$ and $s_r$. The latter relation is furnished by combining Equation [2] with the condition of plane stress ($s_w = 0$), yielding

$$s_t = \frac{s_r \pm \sqrt{4k^2 - 3s_r^2}}{2} \quad [33]$$

Consideration of Equation [30] shows that the choice of sign in Equation [33] should be negative when $r = a$, and positive when $r = b$.

*Procedure for Numerical Solution.* The relation necessary for the solution of Equation [32], giving $w$ as a function of $r$, i.e., the radial distribution of lateral strains in the bent part, is a complex function (see Equation [3]) of the stresses which in turn require for their determination the solution of Equation

[32]. Thus, at the best, an algebraic solution for Equation [32] would be very complex, and even then not adaptable to the solution for an actual (strain-hardenable) metal. Consequently a solution was obtained by a method of successive approximations, each approximation consisting of the steps shown in Table 1, and resulting in a more accurate set of cross sections than the previous set. The final result of any one approximation must be expressed as a set of cross sections, rather than a single one, to represent the increasing "sharpness" of the bend, as expressed by the curvature, $h_0/a$, of the concave surface.

TABLE 1 OUTLINE OF STEPS FOR ONE APPROXIMATION

(a) For the first approximation, assume some arbitrary (but reasonable) set of cross sections which vary in shape with progressive bending. For all succeeding approximations, use the set of cross sections determined by the previous approximation.
(b) Using cross sections given by (a), solve Equation [32] for stresses.
(c) Determine position of neutral axis as point of zero tangential stress.
(d) Using this position of neutral axis and assumed condition of linearly distributed tangential strains, calculate extreme tangential strains.
(e) Determine lateral and radial strains.
(f) Integrate radial strains to obtain height. This, together with distribution of lateral strains, is necessary information for integrating Equation [32], which is first step of next approximation.

The results of the analysis[10] show that the method of successive approximations as outlined is a converging process, i.e., each successive result is closer to a self-consistent final solution than the previous one. The method may be repeated as many times as necessary to obtain the desired accuracy, i.e., until the last and second last set of cross sections differ by less than the accuracy of experimental work.

*Stress and Strain Distributions.* The distributions of radial and tangential stress across the (initially unknown) height are shown in Figs. 12 and 13, respectively, for several curvatures, as calculated by the steps leading to the first approximation. Succeeding approximations yielded similar stress distributions.

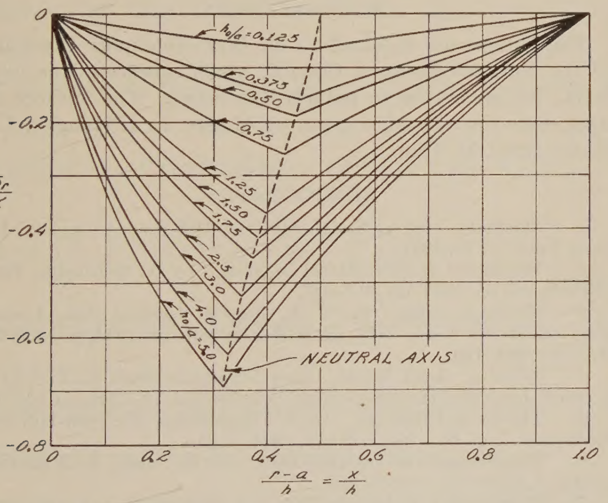

FIG. 12 VARIATION OF RADIAL STRESSES WITH PROGRESSIVE BENDING FOR PLANE STRESS; FIRST APPROXIMATION

The change in position of the neutral axis with changing curvature, Fig. 14, is nearly the same as for plane strain, Fig. 4. The neutral axis remains slightly closer to the center line in plane stress than in plane strain.

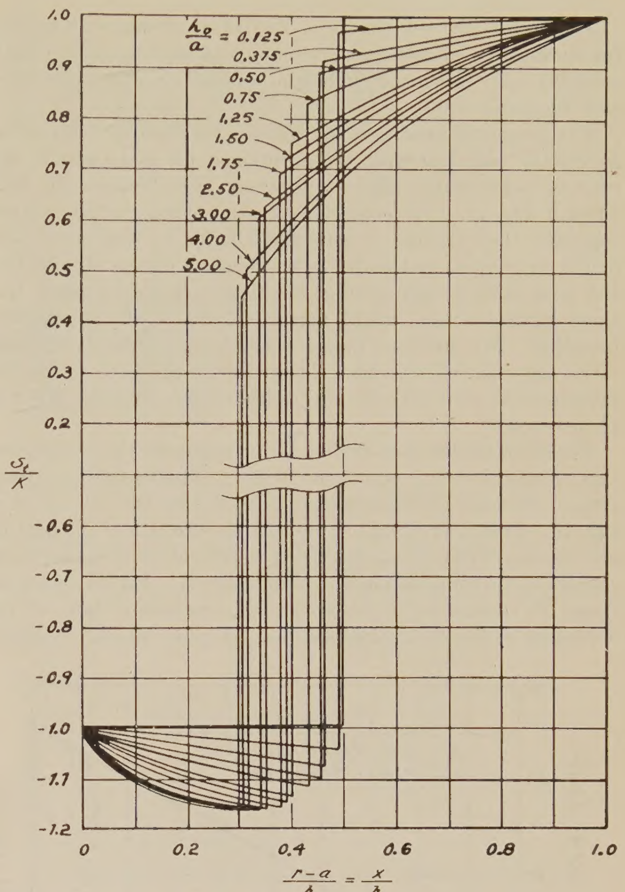

FIG. 13 VARIATION OF TANGENTIAL STRESSES WITH PROGRESSIVE BENDING FOR PLANE STRESS; FIRST APPROXIMATION

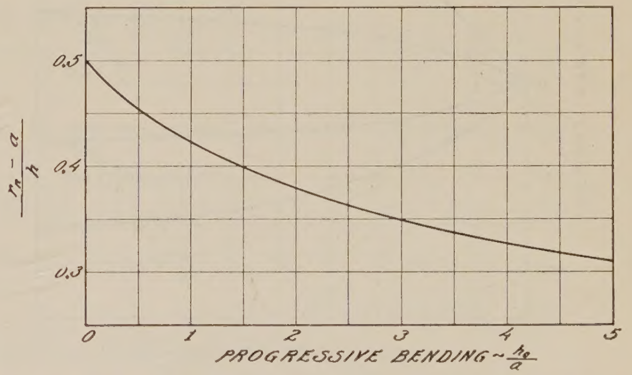

FIG. 14 SHIFT OF NEUTRAL AXIS FOR PLANE STRESS EXPRESSED AS FRACTION OF FINAL HEIGHT; FINAL SOLUTION

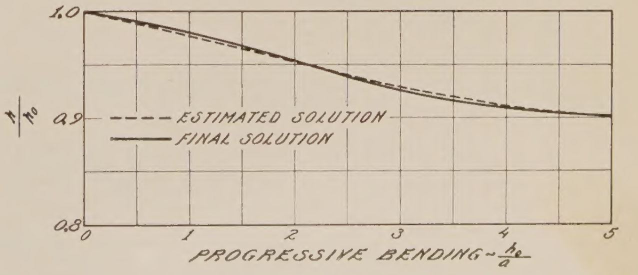

FIG. 15 VARIATION OF HEIGHT FOR PLANE STRESS FOR ESTIMATED AND FINAL SOLUTIONS

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[10] The detailed mathematical procedure of this analysis can be found in Report No. M-478 of the National Defense Research Committee of the Office of Scientific Research and Development entitled "Correlation of Information Available on the Fabrication of Aluminum Alloys (NA-126): Section V—Formability of Aluminum Alloys for Use in Military Aircraft, Part IV—Fundamentals of Pure Bending of an Ideal Plastic Metal Under Conditions of Plane Stress," by G. Sachs, J. D. Lubahn, and J. M. Taub, April 26, 1945.

The height (the solid curve in Fig. 15) decreases with increasing curvature in almost the same manner as in plane strain (Fig. 9, solid curve). The change in height is slightly less for plane stress than for plane strain.

The tangential strains at the concave and convex surfaces are practically identical with those obtained for plane strain, and may be taken with sufficient accuracy directly from the solid curve in Fig. 10. The conditions of plane stress and plane strain represent the extremes of zero and infinity for the breadth-to-height ratio of curved parts. The identical results obtained for the tangential surface strains for these extremes suggest that these surface strains might apply to bars of all intermediate breadths. Fig. 10 shows data for bars having breadth to height ratios between 0.5 and 5.5. These results all agree within the experimental error with the theoretical strains for plane stress or plane strain.

The shape of the cross section can be expressed by the distribution of lateral strains across the height. The variation of these strains with increasing curvature is shown by the solid lines in Fig. 16. It is interesting to note that the breadth of the part increases slowly from the tension side to the center, and then more rapidly as the compression side is approached. Fig. 17 shows the radial distribution of lateral strain for a curvature ($h_0/a$) of 1.3, according to the theoretical solution for plane stress. A condition of plane stress exists in a hypothetical bar whose breadth-to-height ratio is zero. An actual specimen with a very small breadth-to-height ratio (0.1) yielded a radial distribution of lateral strain very nearly that predicted by the theory for plane stress (for the same curvature), Fig. 17. This agreement not only bears out the theoretical analysis, but also indicates that a rather thin strip bent edgewise corresponds closely to a condition of plane stress.

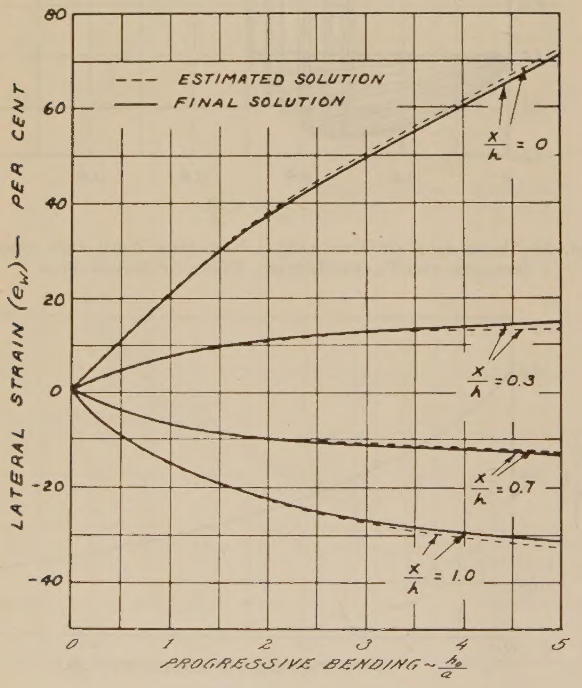

FIG. 16 VARIATION OF LATERAL STRAINS FOR PLANE STRESS FOR ESTIMATED AND FINAL SOLUTIONS

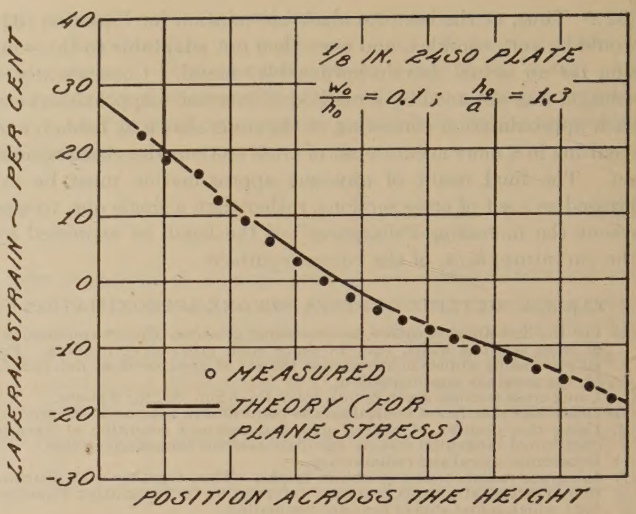

FIG. 17 MEASURED RADIAL DISTRIBUTION OF LATERAL STRAIN FOR $W_0/h_0$ = 0.1 AND THEORETICAL DISTRIBUTION FOR PLANE STRESS

## ACKNOWLEDGMENTS

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